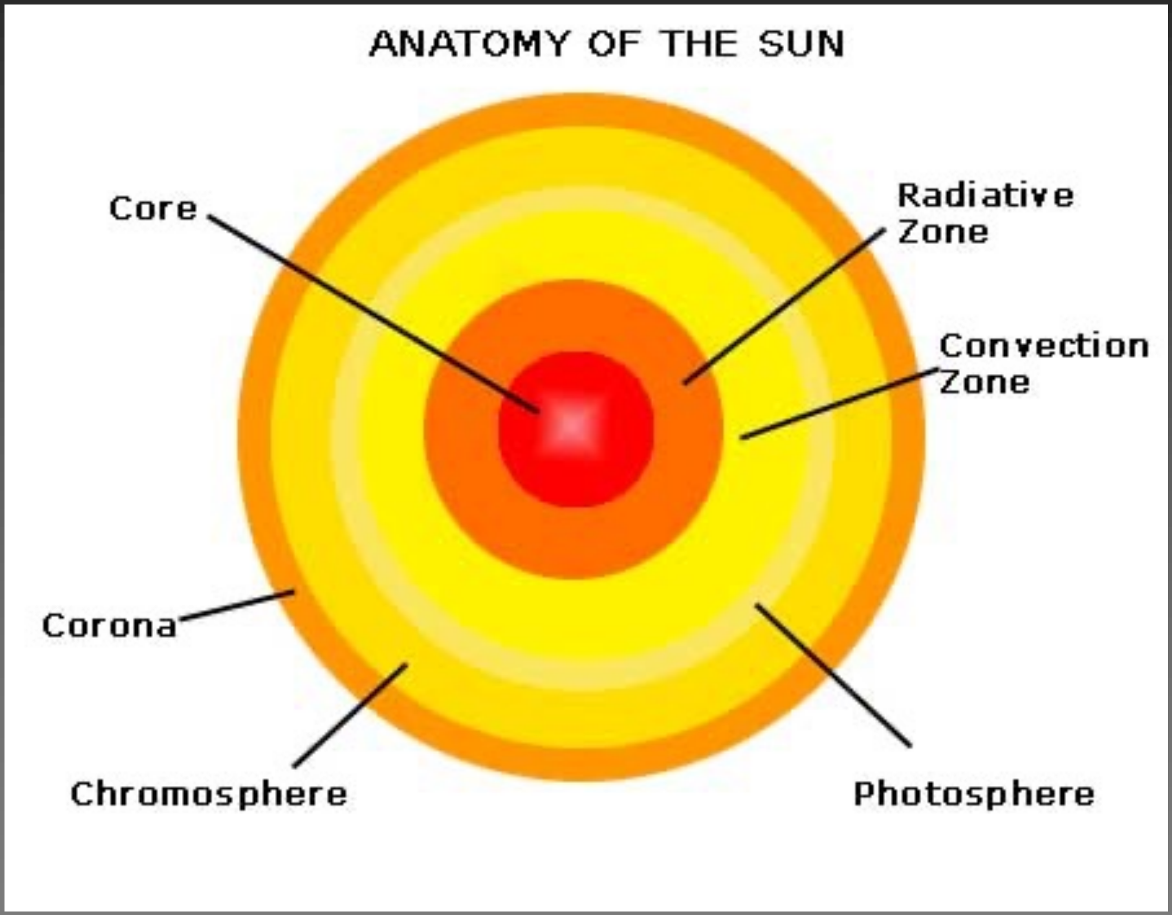
Overall structure



The Sun's atmosphere

- Photosphere: yellowish color. The part we see, T=5800 K.
- The Sun is a giant sphere or gas - so it doesn't have a well defined surface
- Talking about the surface: we mean the photosphere
- The point where atmosphere becomes completely opaque is the photosphere (defines diameter of the Sun)

Solar photosphere as a function of depth

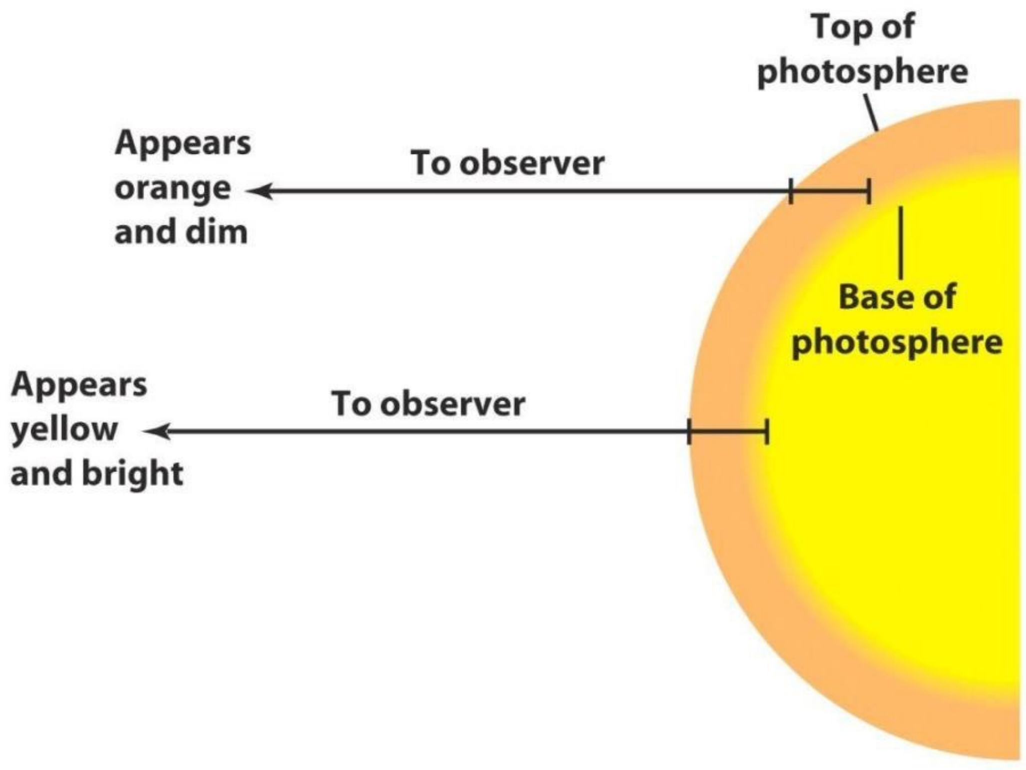
Depth (km)	% Light	Temp (K)	Pressure(bars)
0	99.5	4465	6.8×10^{-3}
100	97	4780	1.7×10^{-2}
200	89	5180	3.9×10^{-2}
250	80	5455	5.8×10^{-2}
300	64	5840	8.3×10^{-2}
350	37	6420	1.2×10^{-1}
375	18	6910	1.4×10^{-1}
400	4	7610	1.6×10^{-1}

Limb darkening

- Outer portions of photosphere being cooler
- Photons travel about the same path length

Dimmer light comes from higher, relatively cool layer within the photosphere

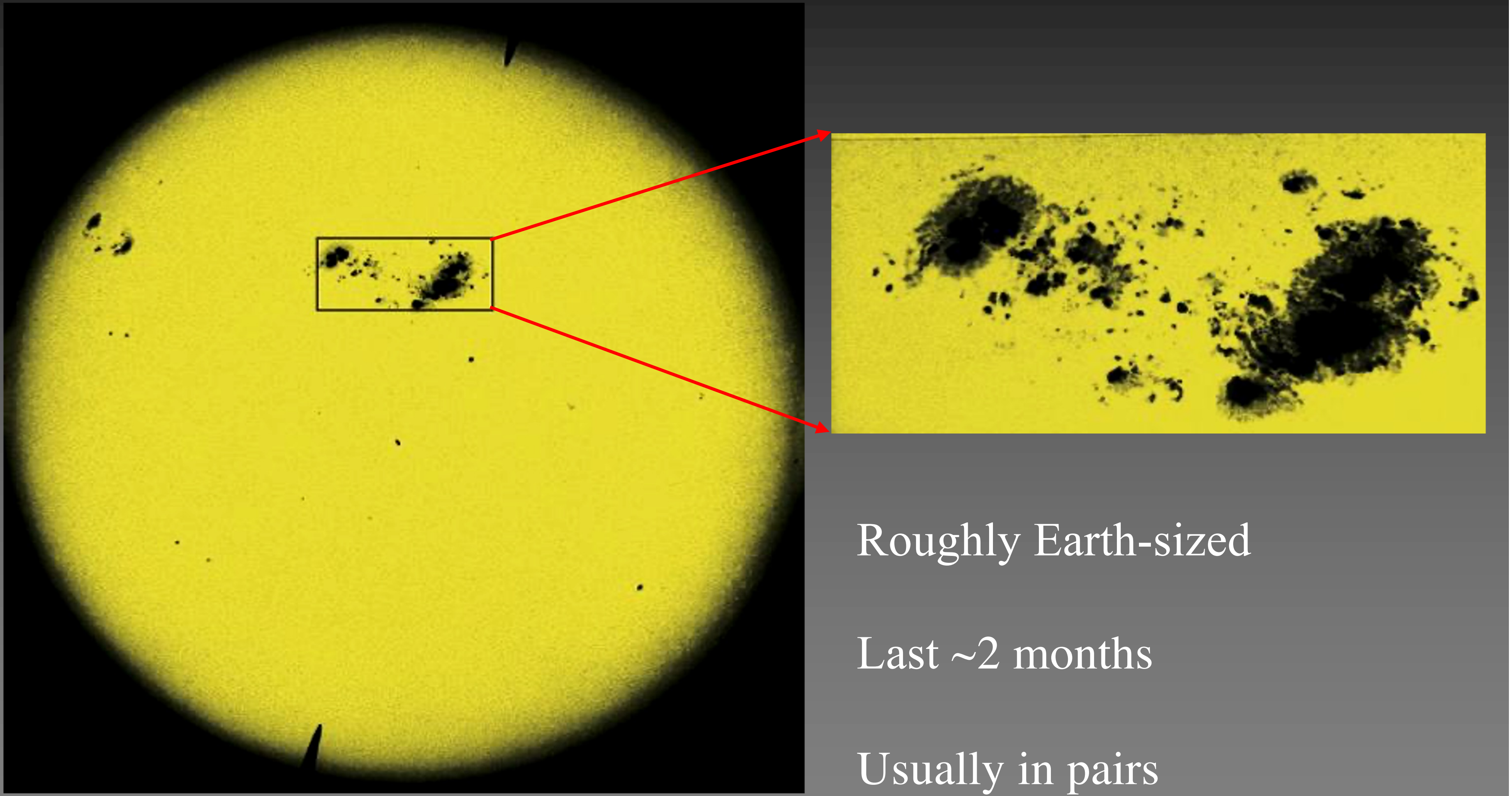
Bright light comes from low-lying, hot layer within the photosphere



- For something not having a well defined surface, it doesn't look very fuzzy, it looks well defined?

- We see about 400 km into photosphere - a tiny distance (0.06%) compared to radius (696,000 km) so looks sharp ("unresolved" to eyes).

Sunspots

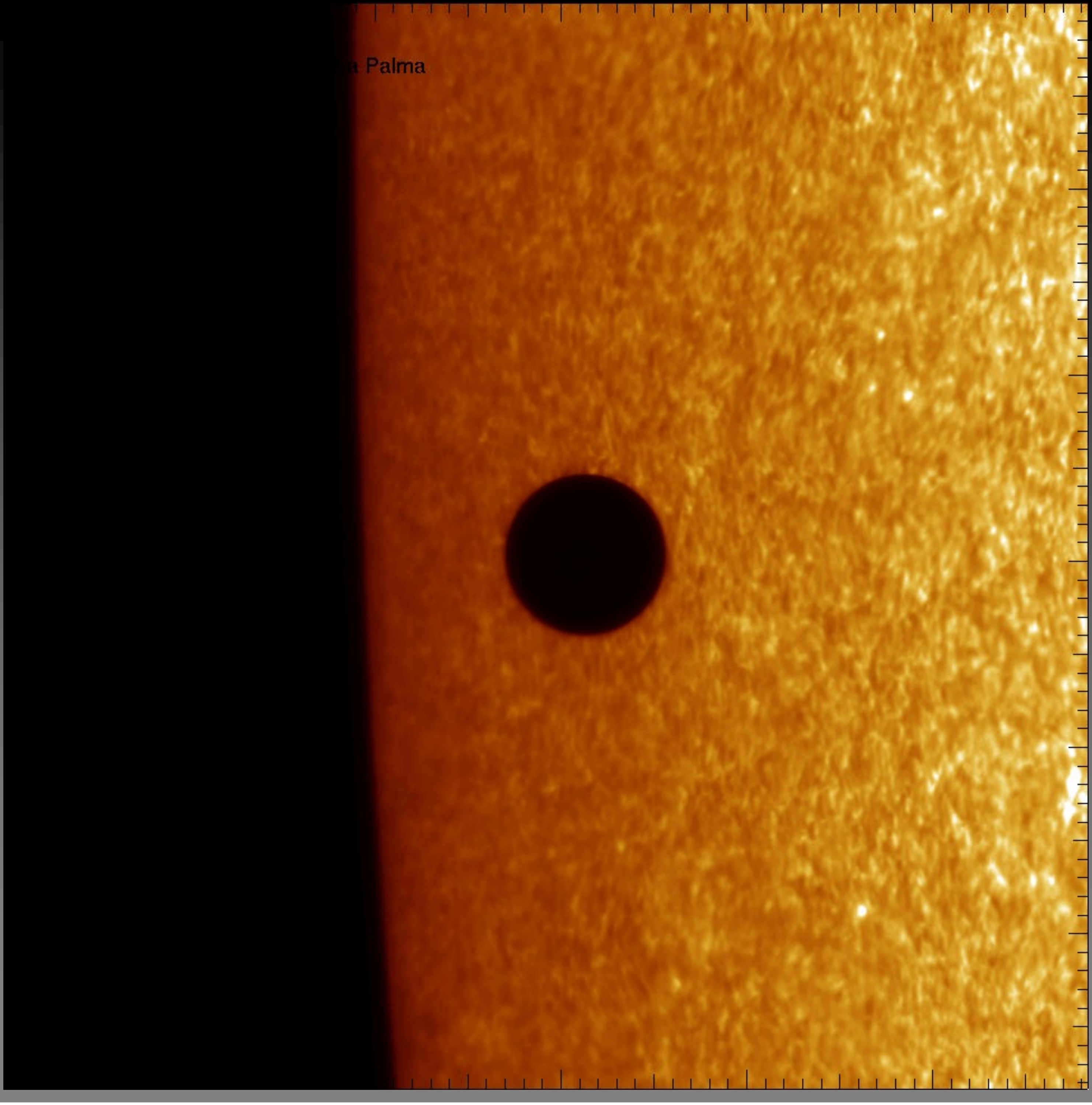


Roughly Earth-sized

Last ~2 months

Usually in pairs

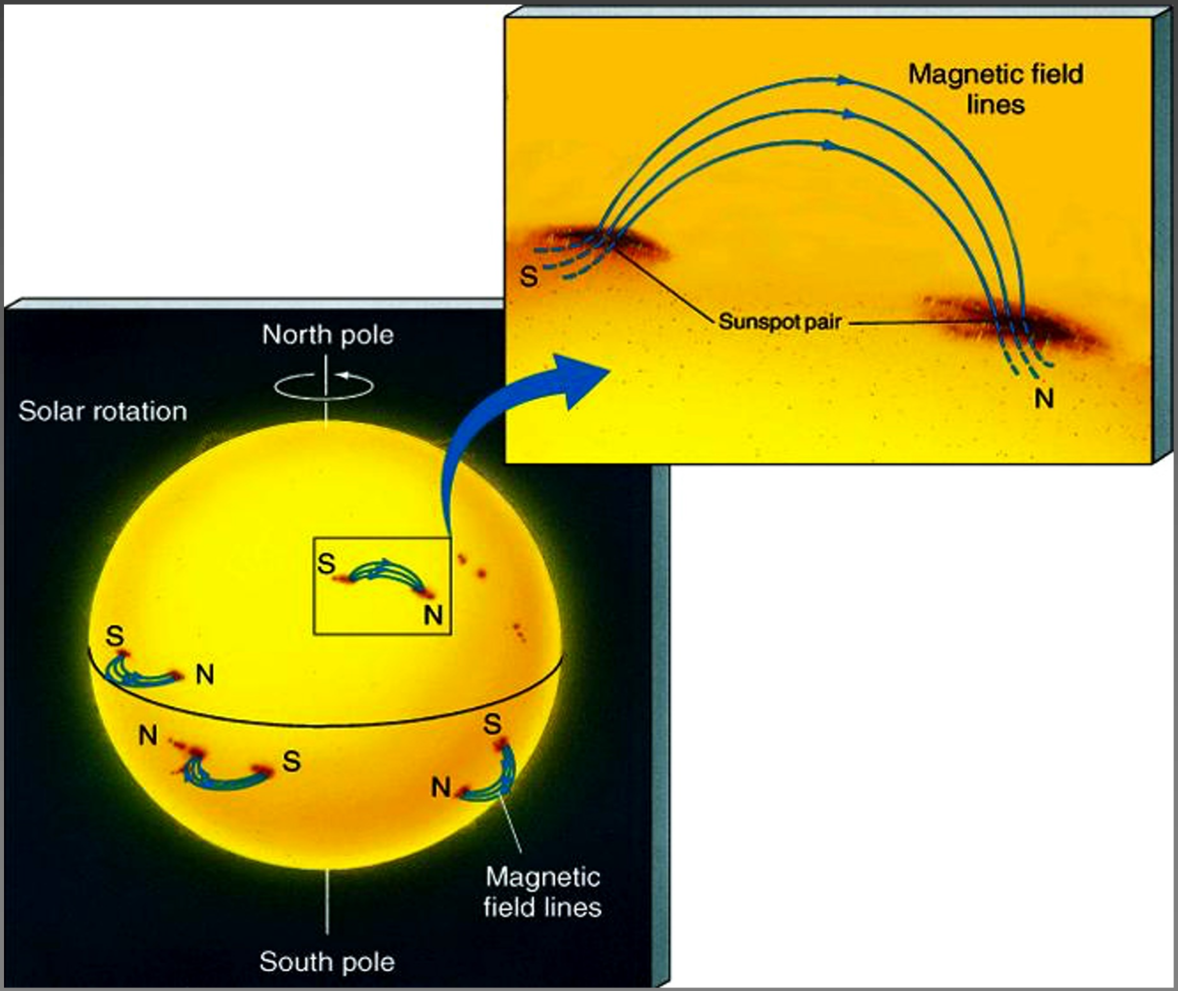
Follow solar rotation


a Palma

Sunspots

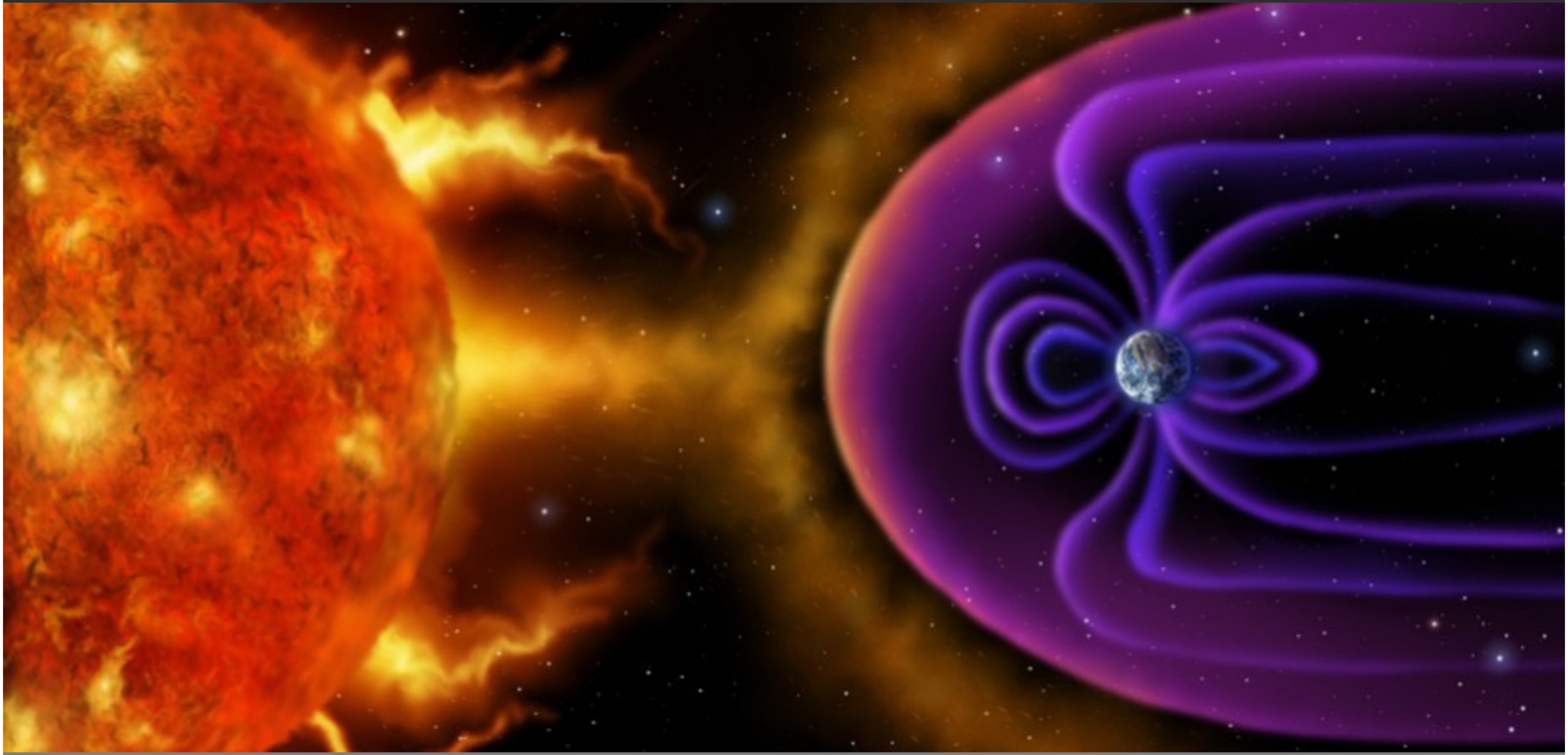
They are darker because they are cooler (4500 K vs. 5800 K).

Related to loops of the Sun's magnetic field.

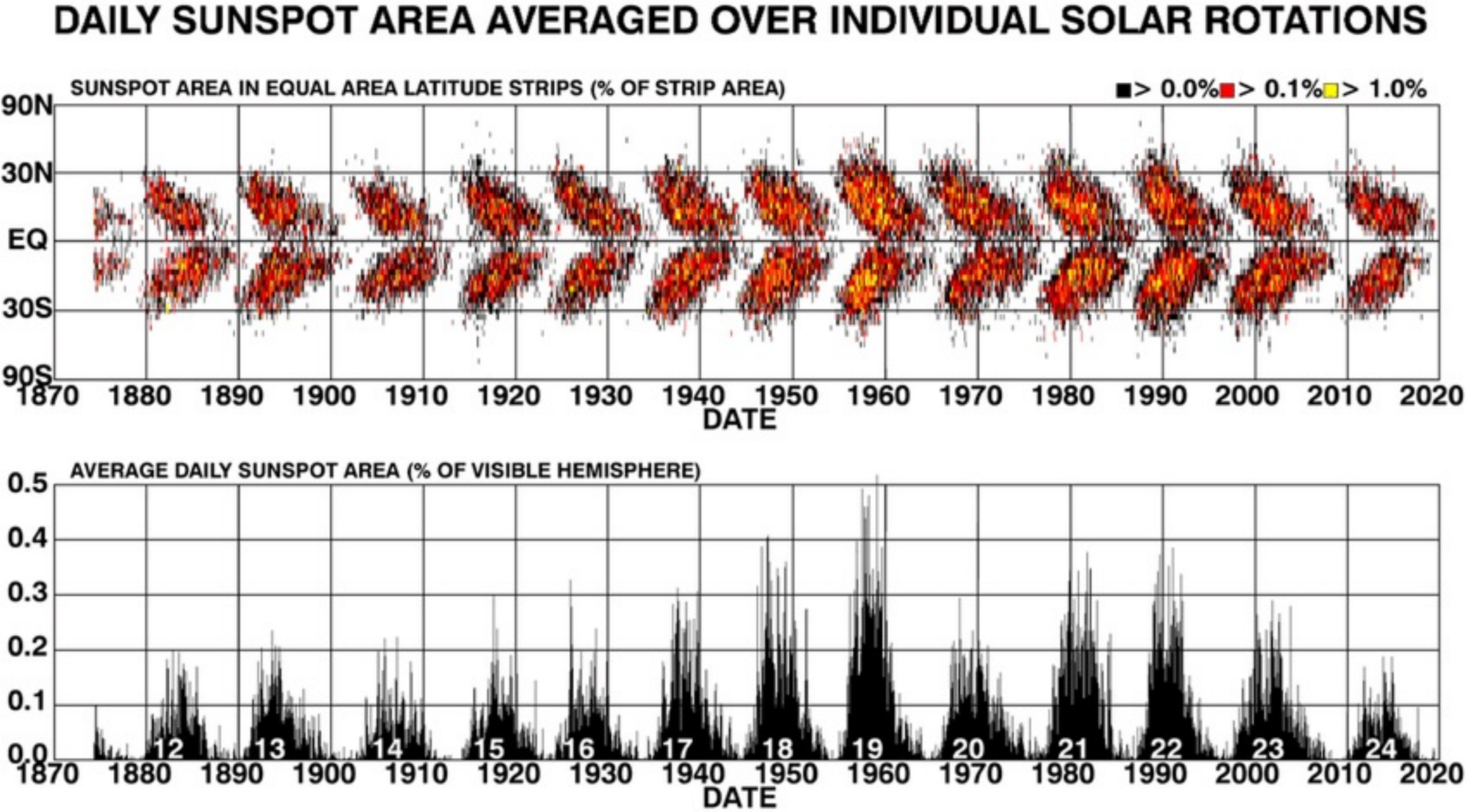


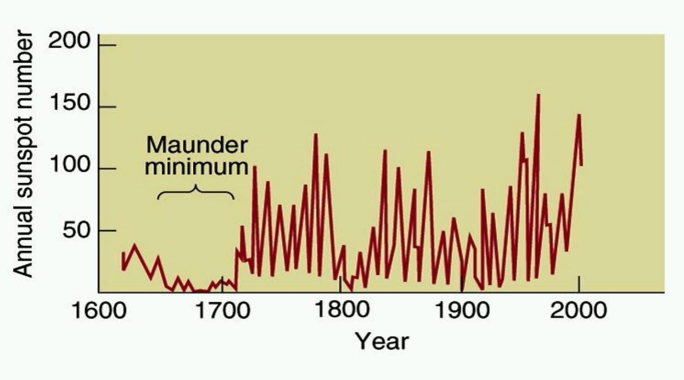
radiation from hot gas flowing along magnetic field loop at limb of Sun.

Solar Storms!

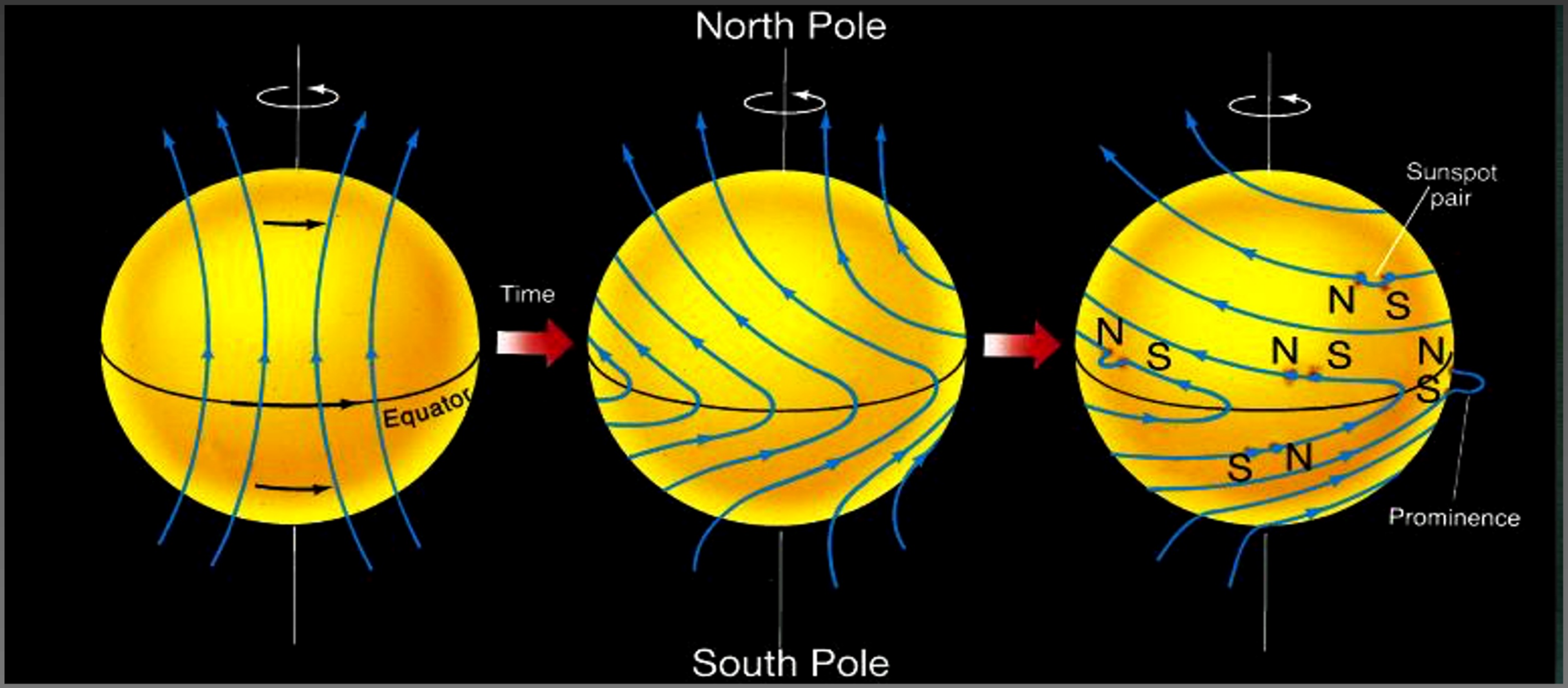


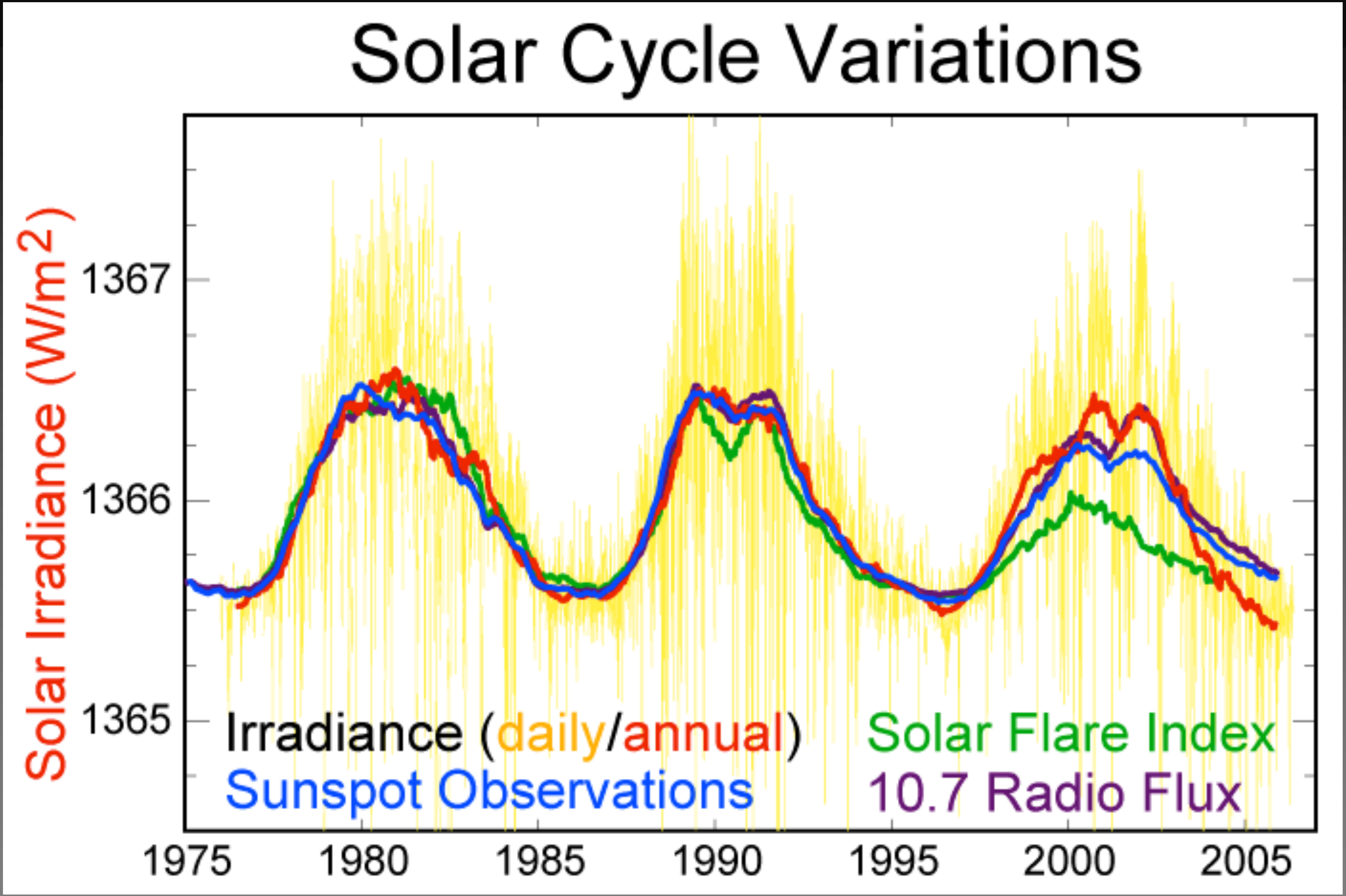
Sunspot numbers vary on a 11 year cycle.





Sun's magnetic field changes direction every 11 years. Maximum sunspot activity occurs about halfway between reversals.



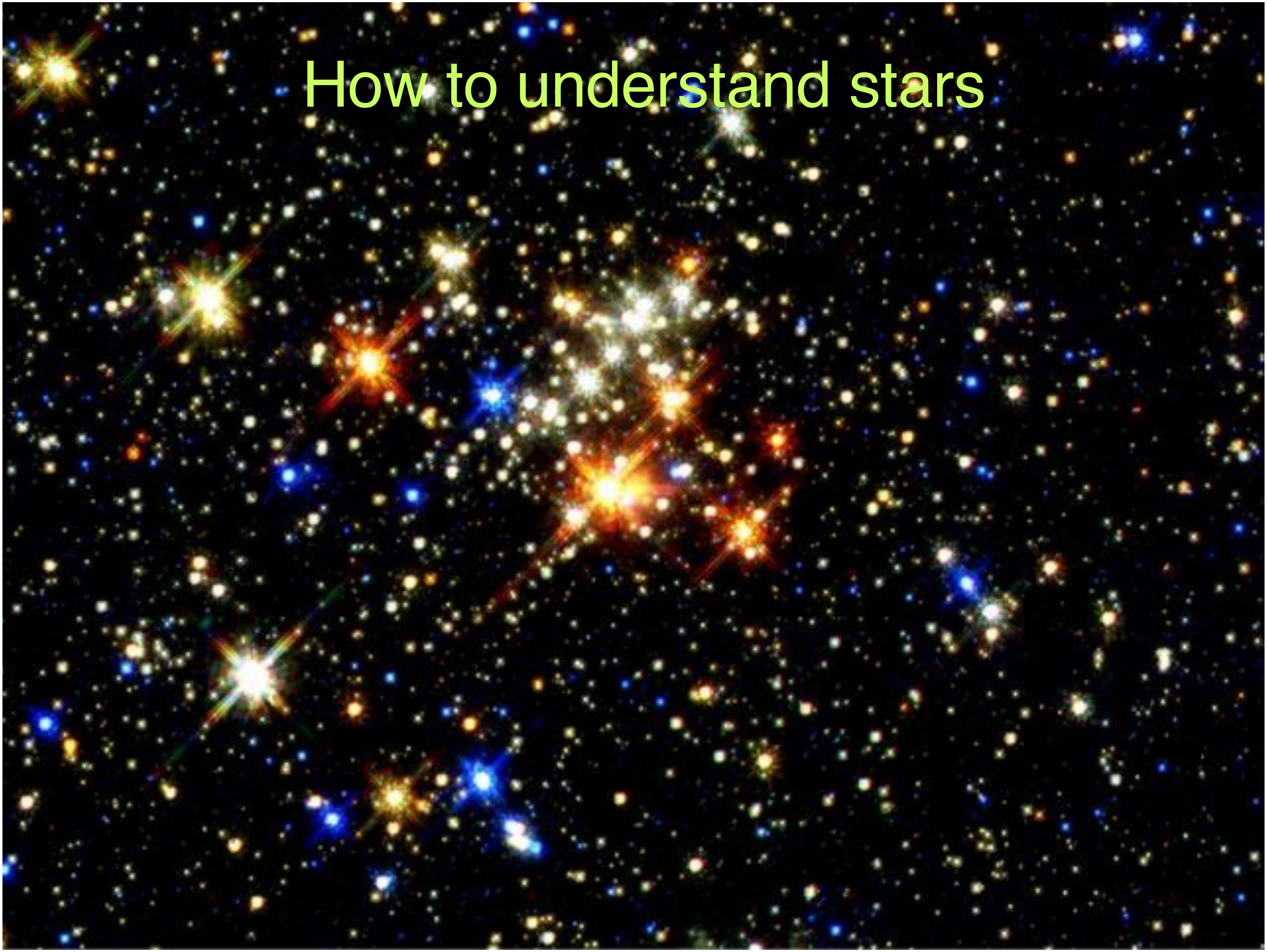


0.1% variation from maximum to minimum

Announcements

- Homework #2 due Thursday.
- VLA Tour Saturday Sept 28. 8am – 4pm, lunch provided
- How many can go? Can drive?

How to understand stars



What are stars?

Are they all alike?

Is the Sun typical?

Picture of Orion illustrates:

- The huge number of stars
- Colors
- Interstellar gas

How can we describe/classify stars?

- Temperature
- Luminosity (total energy output)
- Mass (orbital motion)
- Physical sizes
- True motion in space

To estimate those parameters, we need to know the distance!

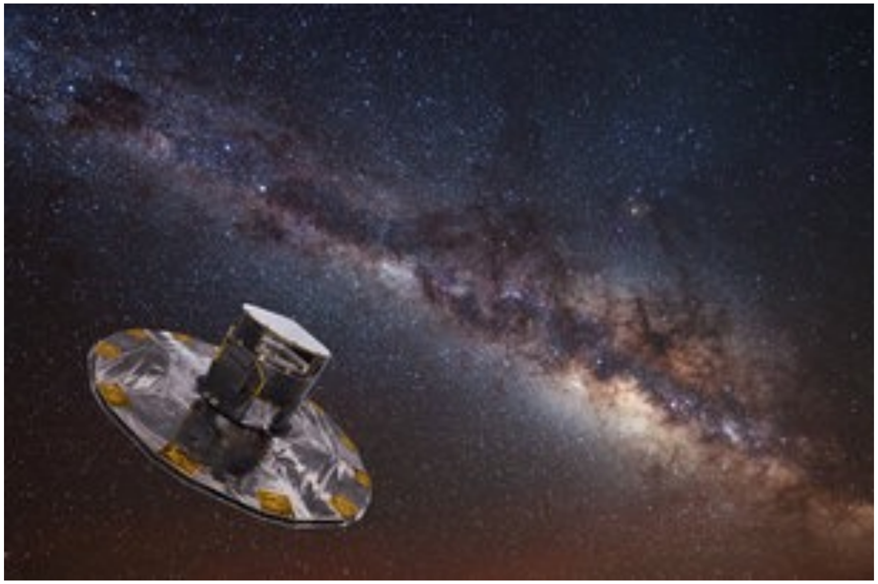
The parallax formula for distance

- $d = 1/p$ where p is the parallax angle and d is the distance in pc.
- Distance units: 1 pc = 3.26 ly = $3.09\text{x}10^{16}$ m = 206,265AU
- It took us until 1838 to measure stellar parallaxes since the stars are so far away => small parallax angles

Limitations

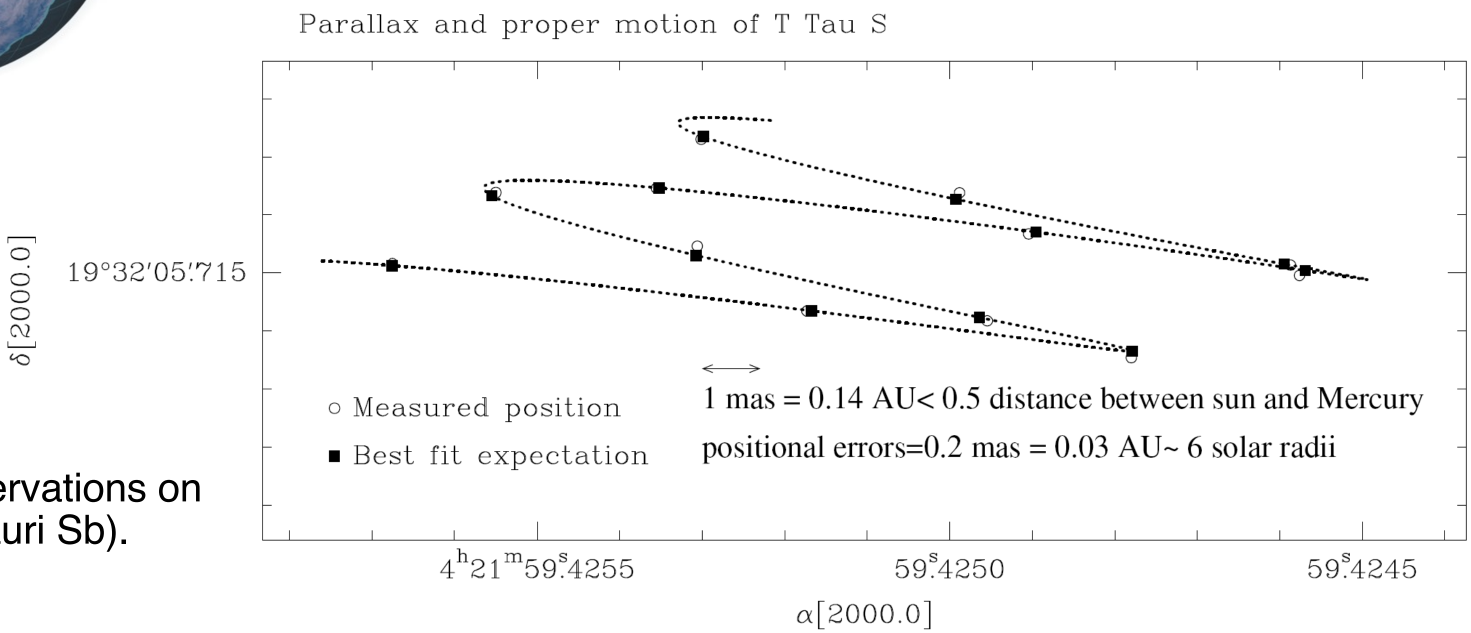
- Until recently we only knew accurate (0.01") parallaxes for a few 100 stars (=> d~100pc)
- In the 1990's the ESA satellite Hipparchos measured over 100,000 parallaxes with an accuracy of 0.001"
- Gaia has measured over a billion stars to 2 kpc
- With VLBI we can measure 10μas parallaxes

Gaia satellite



Astrometry with VLBI

VLBI=Very Log Baseline Interferometry, more on this later in the radio astronomy lecture



1 mas = 0.14 AU< 0.5 distance between sun and Mercury

positional errors=0.2 mas = 0.03 AU~ 6 solar radii

Distance=147.5 ±0.8 pc

Loinard et al. (2006)

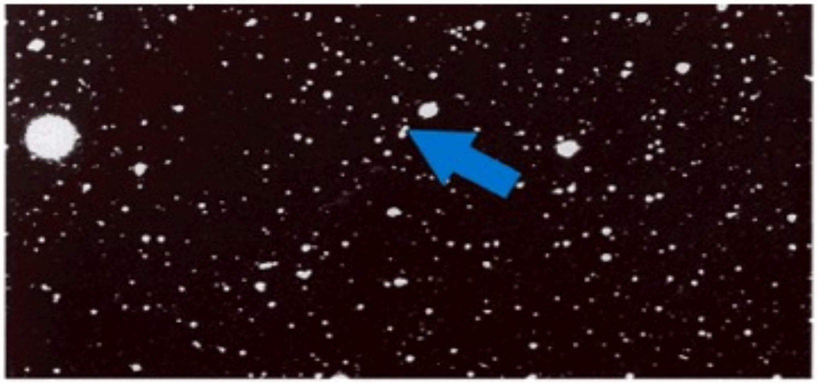
12 epochs of observations on a young star (T Tauri Sb).

Why is the star not outlining an ellipse on the sky?

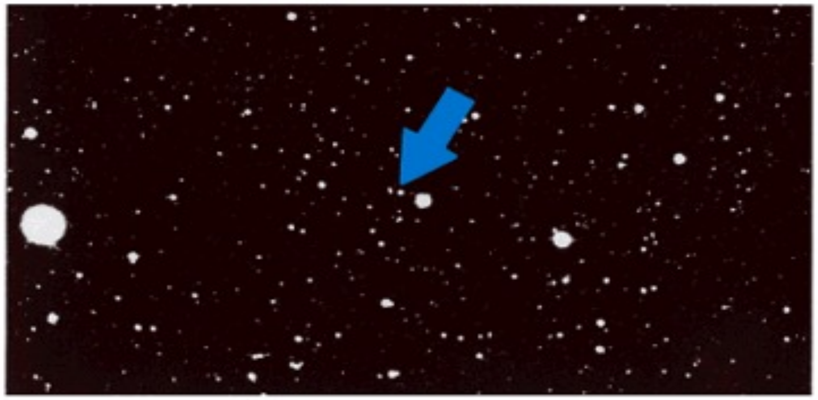
Because of *proper motion*.

Proper motion

- Caused by physical movement of a star with respect to our Solar system
- This is in contrast to parallax which is an apparent motion of the star due to the motion of the Earth
- Proper motion is the angle a star moves per year (angular motion on the sky), and it is a linear drift
- The superposition of this linear drift and the elliptical motion from the parallax effect leads to a 'wavy' path on the sky



August 24, 1894



May 30, 1916

This star moved 4' over this time - a huge proper motion of 10˝.9/yr.

Tangential velocity

$v_t = 4.74\,\mu d$, where μ is the proper motion [″/yr] and d is the distance [pc]; this choice of constants gives v_t in the units of km/s.

Dependent on distance

Radial velocity

Given by Doppler shift:

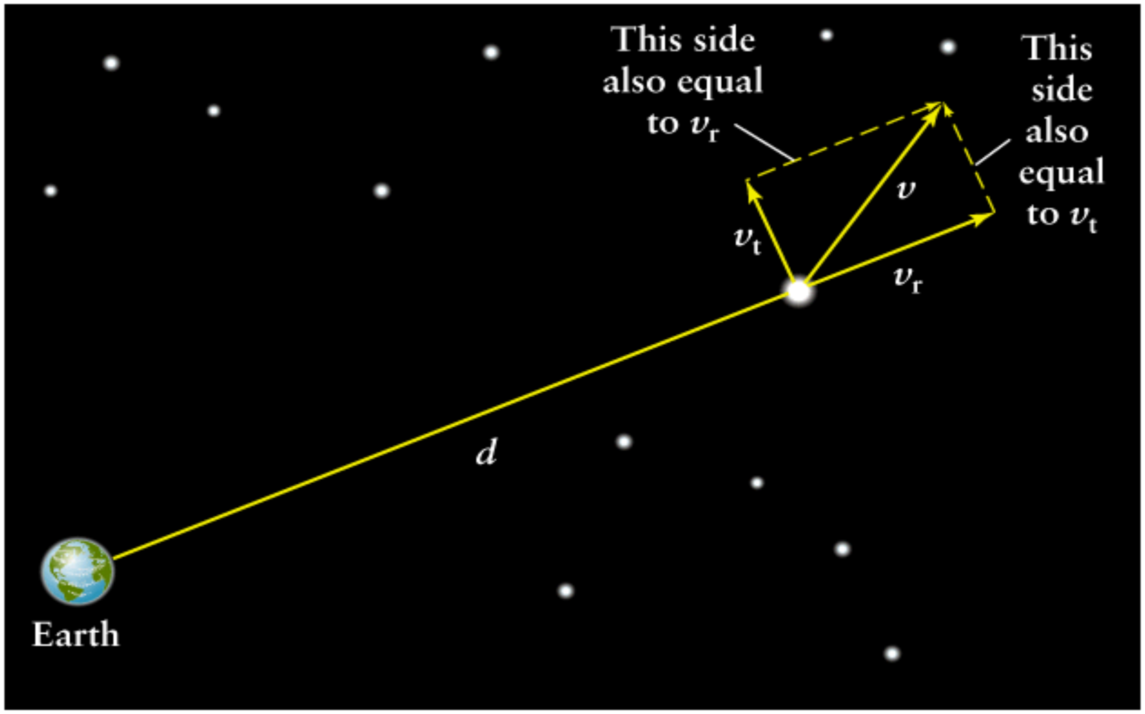
$v_r = [(\lambda_{\text{observed}} - \lambda_{\text{emitted}}) / \lambda_{\text{emitted}}]\, c$

Independent on distance

Space Velocity

Speed and direction of star. From Pythagorean theorem

$$V = \sqrt{V_t^2 + V_r^2} = \sqrt{(4.74\mu d)^2 + V_r^2}$$



Typical stellar space velocities are 20-100 km/s.

Three quantities need to be measured - distance is the most difficult one.

Why care about stellar motions?

- A tool to study structure of our Galaxy
    - Motion of the Sun (towards constellation of Hercules with 20km/s)
    - Rotation of the Galactic Plane (local)
    - Odd phenomena/stars that might indicate special events
    - Past merger events

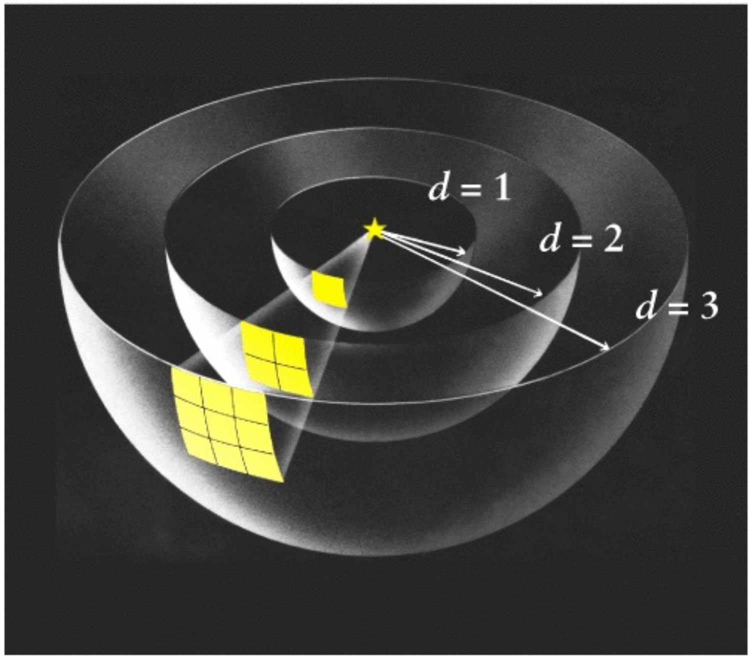
How bright is a star?

- Luminosity (*L,* intrinsic property): the total energy output, a physical property of the star. Doesn't depend on distance.

- Apparent brightness (*F,* or *b*): measures how bright a star appears to be on a distance. Does depend on distance!

- The brightness, or intensity, of light diminishes as the inverse square of the distance.

$$F = L/4\pi d^2$$



Same amount of radiation from a star must illuminate a bigger area as distance from star increases.The area increases as the square of the distance.

Apparent magnitudes

- Measurement of brightness of stars as they seem from Earth.

- Smaller magnitudes mean brighter stars and defined such that 5 magnitude differences implies a factor of 100 in brightness

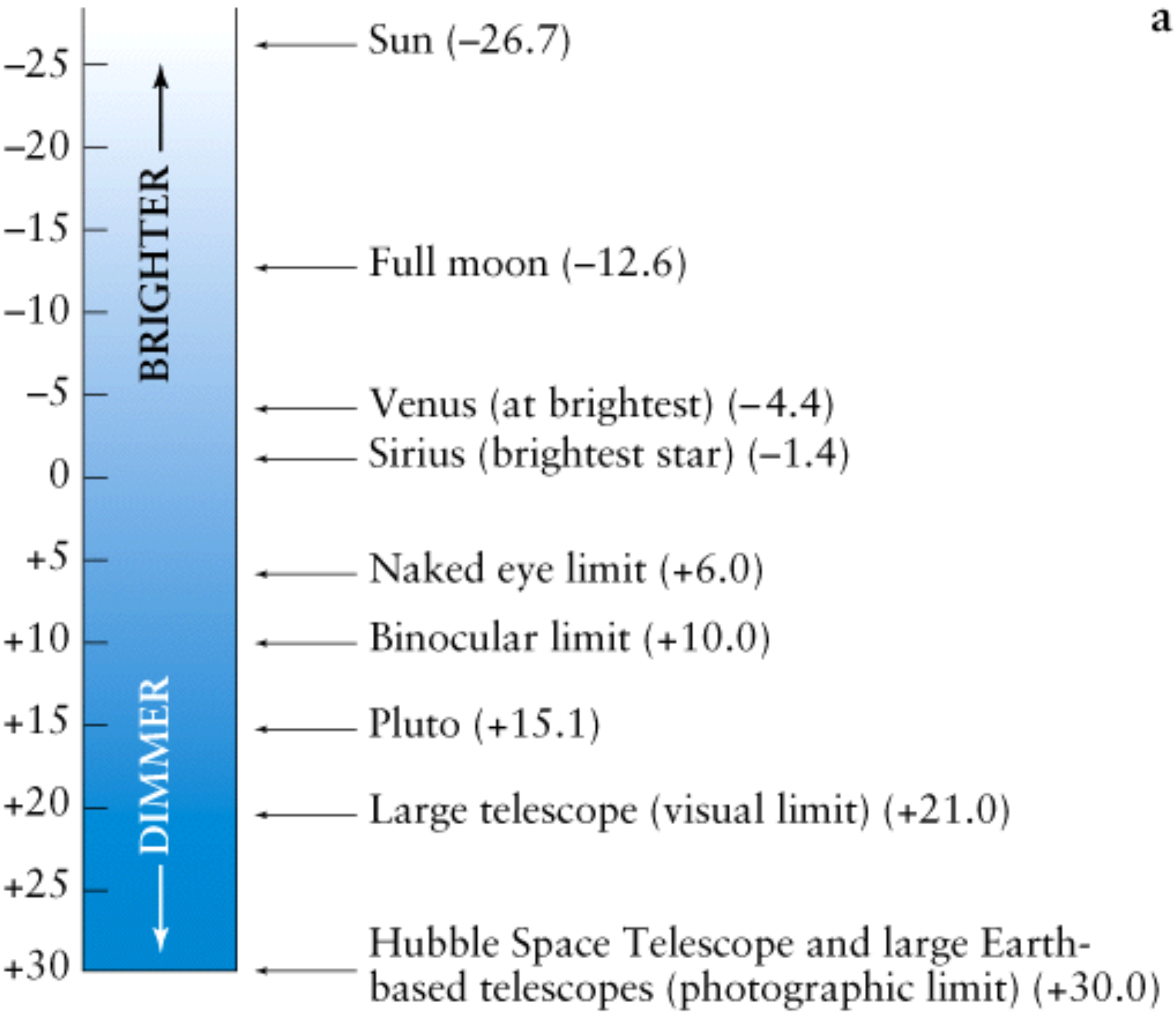
- Magnitude difference related to brightness ratio:

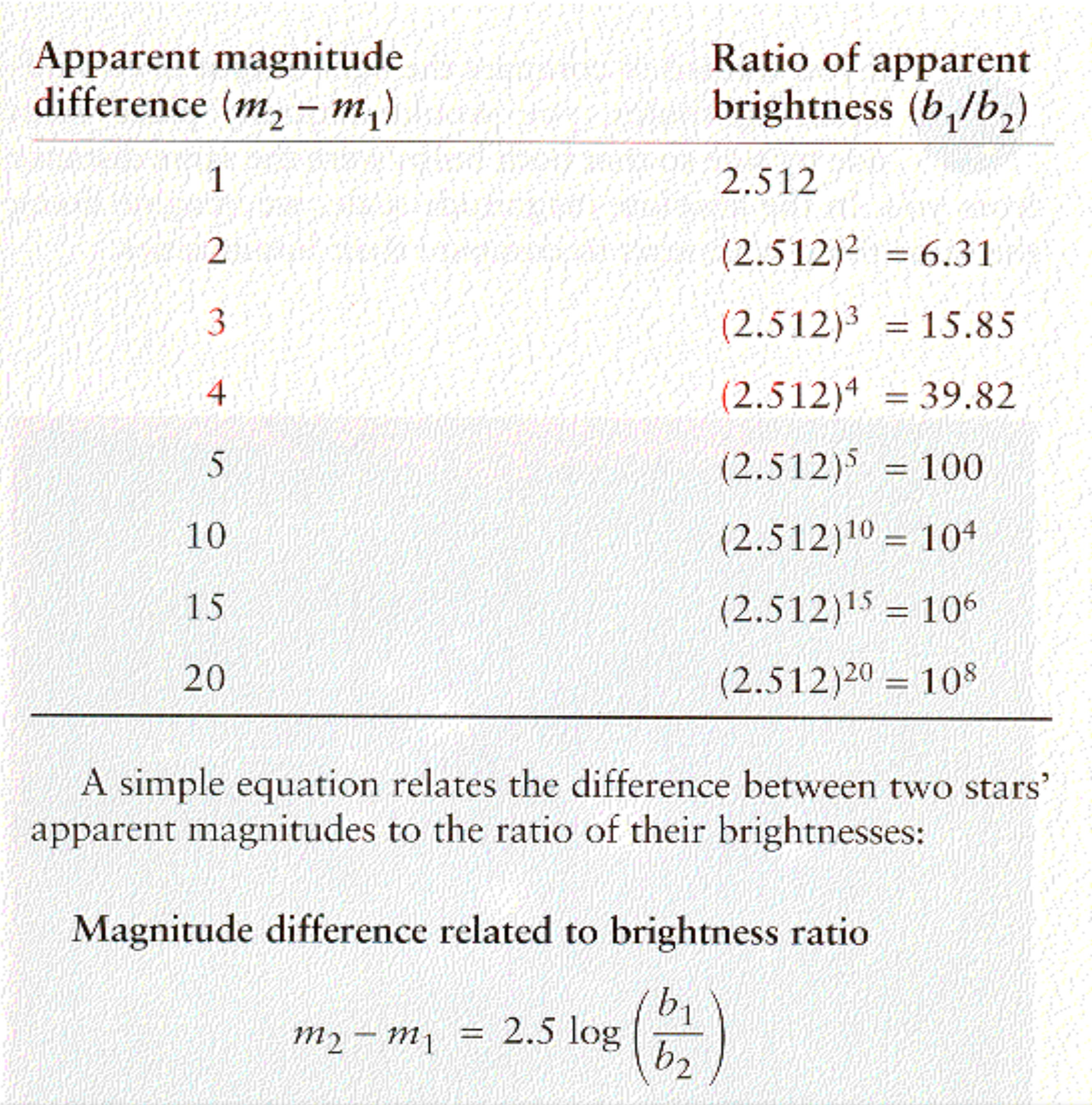
$$m_2 - m_1 = 2.5\log\left(\frac{b_1}{b_2}\right)$$

- Also note: if $\frac{b_1}{b_2} = 100$, then $2.5\log\left(\frac{b_1}{b_2}\right) = 5$

- This is a logarithmic scale - no zero point is defined. Done by defining certain stars to have zero magnitude.

The apparent magnitude scale - some examples:





Apparent magnitude difference ($m_2 - m_1$)	Ratio of apparent brightness (b_1/b_2)
1	2.512
2	$(2.512)^2 = 6.31$
3	$(2.512)^3 = 15.85$
4	$(2.512)^4 = 39.82$
5	$(2.512)^5 = 100$
10	$(2.512)^{10} = 10^4$
15	$(2.512)^{15} = 10^6$
20	$(2.512)^{20} = 10^8$

A simple equation relates the difference between two stars' apparent magnitudes to the ratio of their brightnesses:

Magnitude difference related to brightness ratio

$$m_2 - m_1 = 2.5 \log\left(\frac{b_1}{b_2}\right)$$

A factor of 2.512 difference in brightness per magnitude. Box 17-3.

Absolute magnitude

Caution:

Apparent magnitude is NOT power output! A star may have bright (small) apparent magnitude because it is close to us, or it might have a bright (small) magnitude because it produces a huge amount of light.

As scientists, we want a brightness scale that takes distance into account and measures the *total* energy output of the star.

Absolute magnitude:

Definition: the apparent magnitude a star would have if it were precisely 10 pc away from us

$$m - M = 5\log(d) - 5$$

m is apparent magnitude (measured)

d is distance (calculated from parallax)

M is absolute magnitude

The absolute magnitude is a more useful measure of a star’ s power output (Luminosity).

Examples:

M	Star
-5	Betelgeuse
-1.5	Sirius
+5	Sun
+10	Sirius B

Since $L = 4\pi d^2 b$, we can compare any star's luminosity to the Sun's by a ratio:

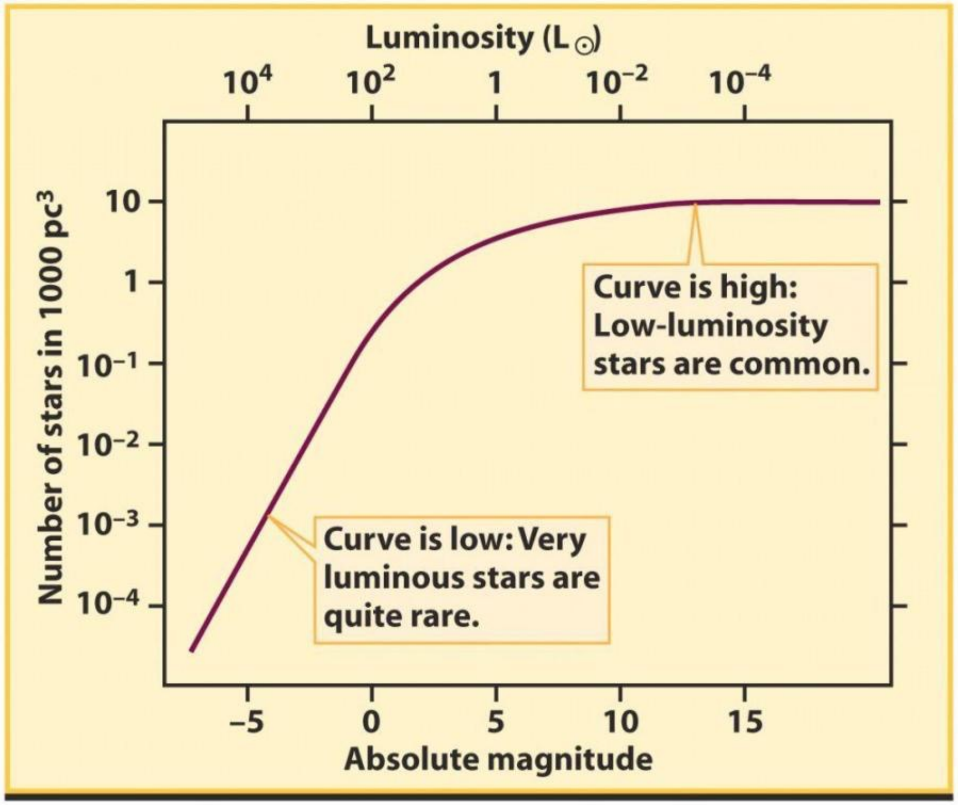
$$\frac{L_*}{L_{Sun}} = \frac{4\pi d_*^2 b_*}{4\pi d_{sun}^2 b_{Sun}} = \left(\frac{d_*}{d_{Sun}}\right)^2 \frac{b_*}{b_{Sun}}$$

Knowing relative distance and brightness, we know the star's relative luminosity. Finally, you can show that

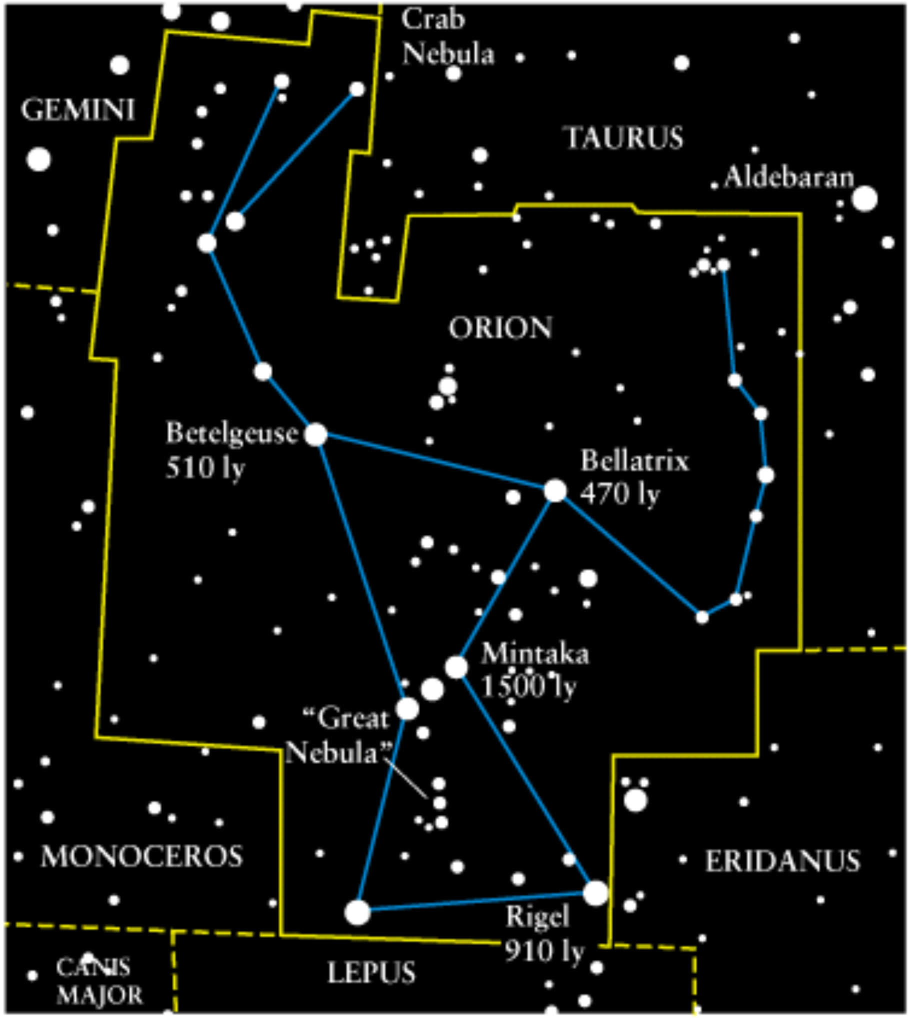
$$M_{Sun} - M_* = 2.5\log\frac{L_*}{L_{Sun}}$$

Luminosity function

- Describes the relative numbers of stars with different luminosities
- There are more faint stars than bright
- Note the enormous range in luminosity



Are you seeing neighbor stars, or highly luminous (but distant) stars?

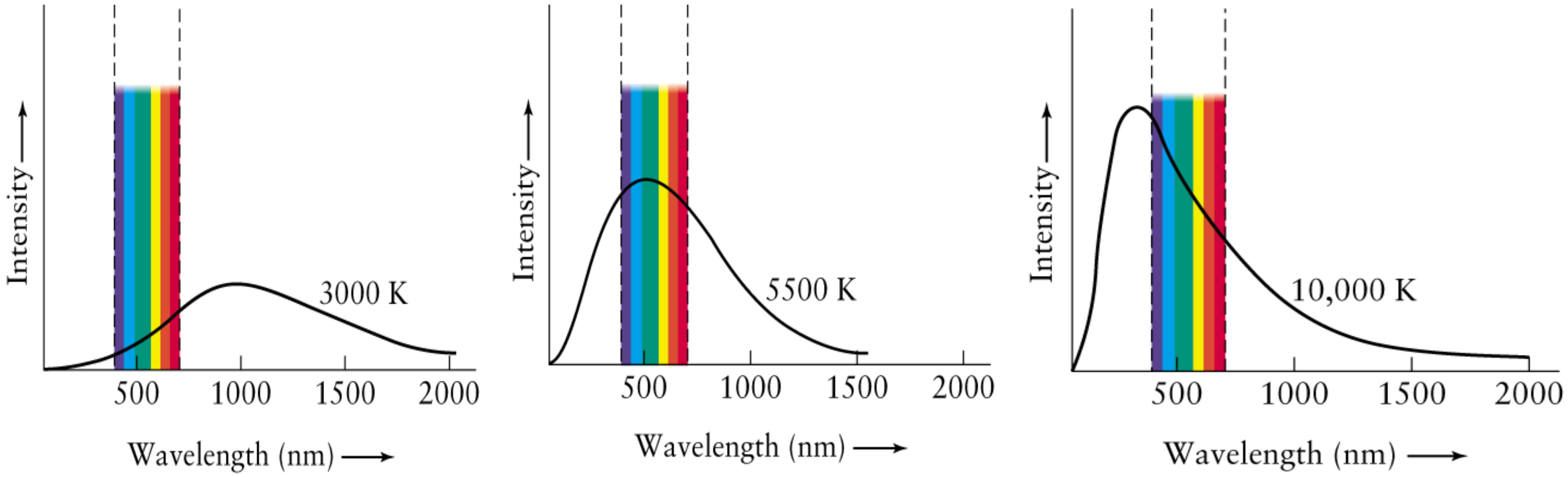


b

Recall that 1 pc is 3.26 ly. E.g. Betelgeuse is about 160 pc away.

Colors of stars

- From Wien's law $\lambda_{max} = 0.0029/T$ we expect hotter objects to be bluer.



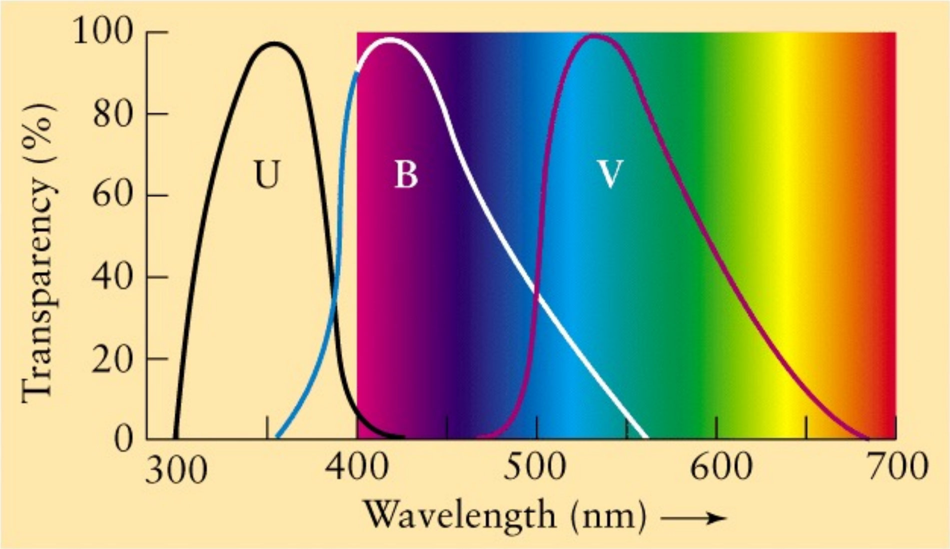
a This star looks red

b This star looks yellow-white

c This star looks blue-white

To measure colors

- A set of filters can be used to determine the colors of stars



The UBV system

- In fact, we don't need distances - apparent magnitudes in each filter works
- If a B magnitude is small, does that mean that the star is very blue?
  - Not necessarily, the V and R magnitudes might be even smaller. Then the star is brighter in redder filters.

To quantify color: color index

- Need brightness measurements through at least 2 filters to determine color
- Example: B-V color index

$$CI = B - V = 2.5\log\left(\frac{b_V}{b_B}\right) + const$$

- The constant is chosen so that a star at 10^4 K has a B-V = 0.0

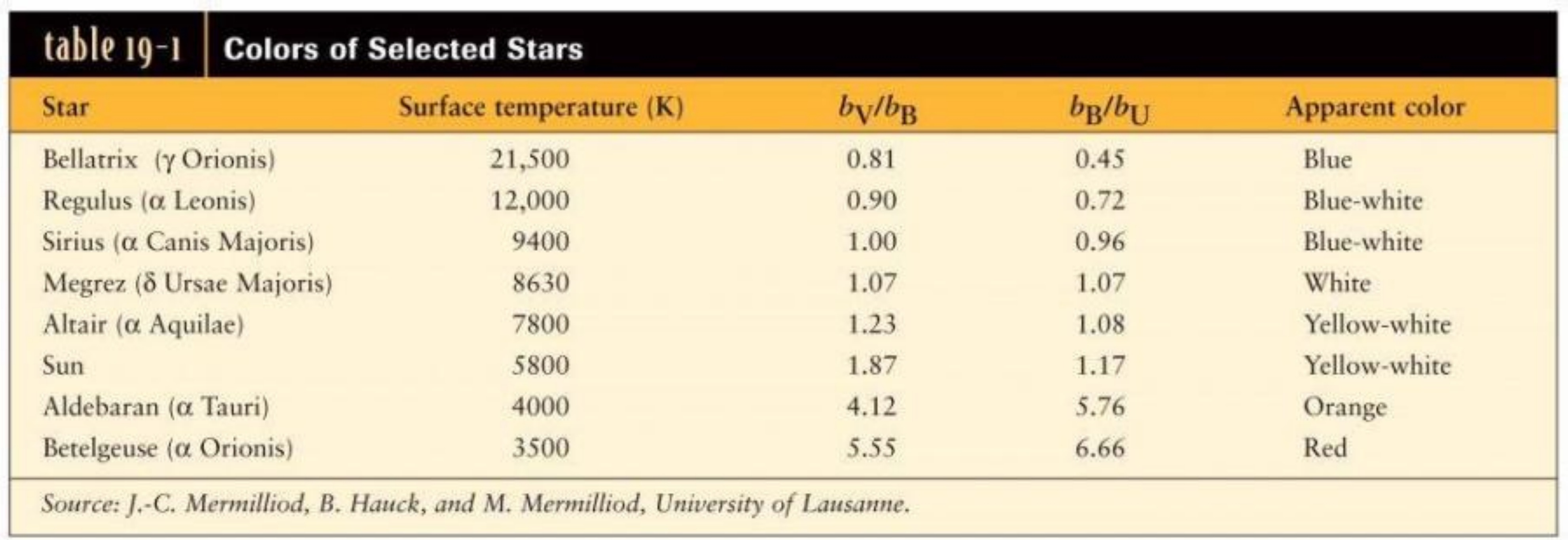
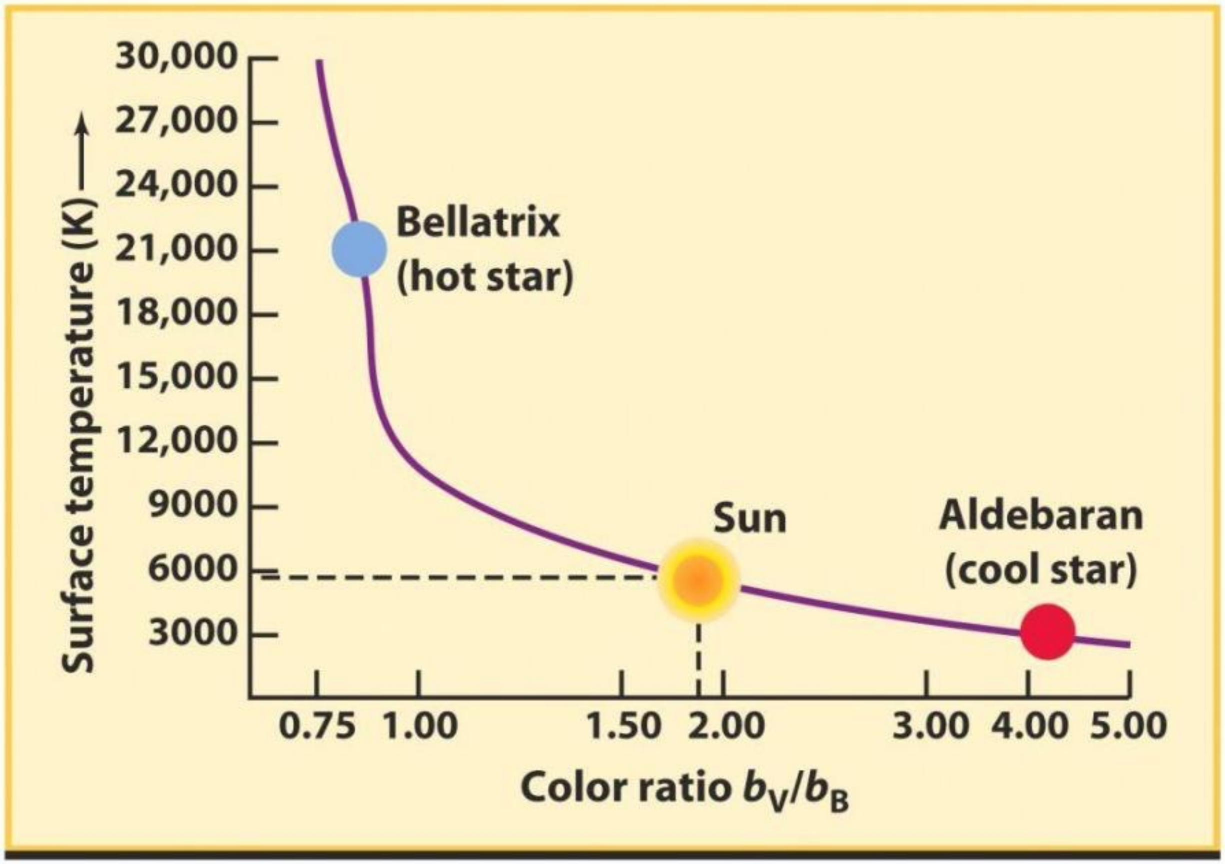


table 19-1 Colors of Selected Stars

Star	Surface temperature (K)	b_V/b_B	b_B/b_U	Apparent color
Bellatrix (γ Orionis)	21,500	0.81	0.45	Blue
Regulus (α Leonis)	12,000	0.90	0.72	Blue-white
Sirius (α Canis Majoris)	9400	1.00	0.96	Blue-white
Megrez (δ Ursae Majoris)	8630	1.07	1.07	White
Altair (α Aquilae)	7800	1.23	1.08	Yellow-white
Sun	5800	1.87	1.17	Yellow-white
Aldebaran (α Tauri)	4000	4.12	5.76	Orange
Betelgeuse (α Orionis)	3500	5.55	6.66	Red

Source: J.-C. Mermilliod, B. Hauck, and M. Mermilliod, University of Lausanne.

Temperature, color and color ratio



- The b_V/b_B color ratio is small for hot stars, and large for cool stars.

What are stars?

Are they all alike?

Is the Sun typical?

Picture of Orion illustrates:

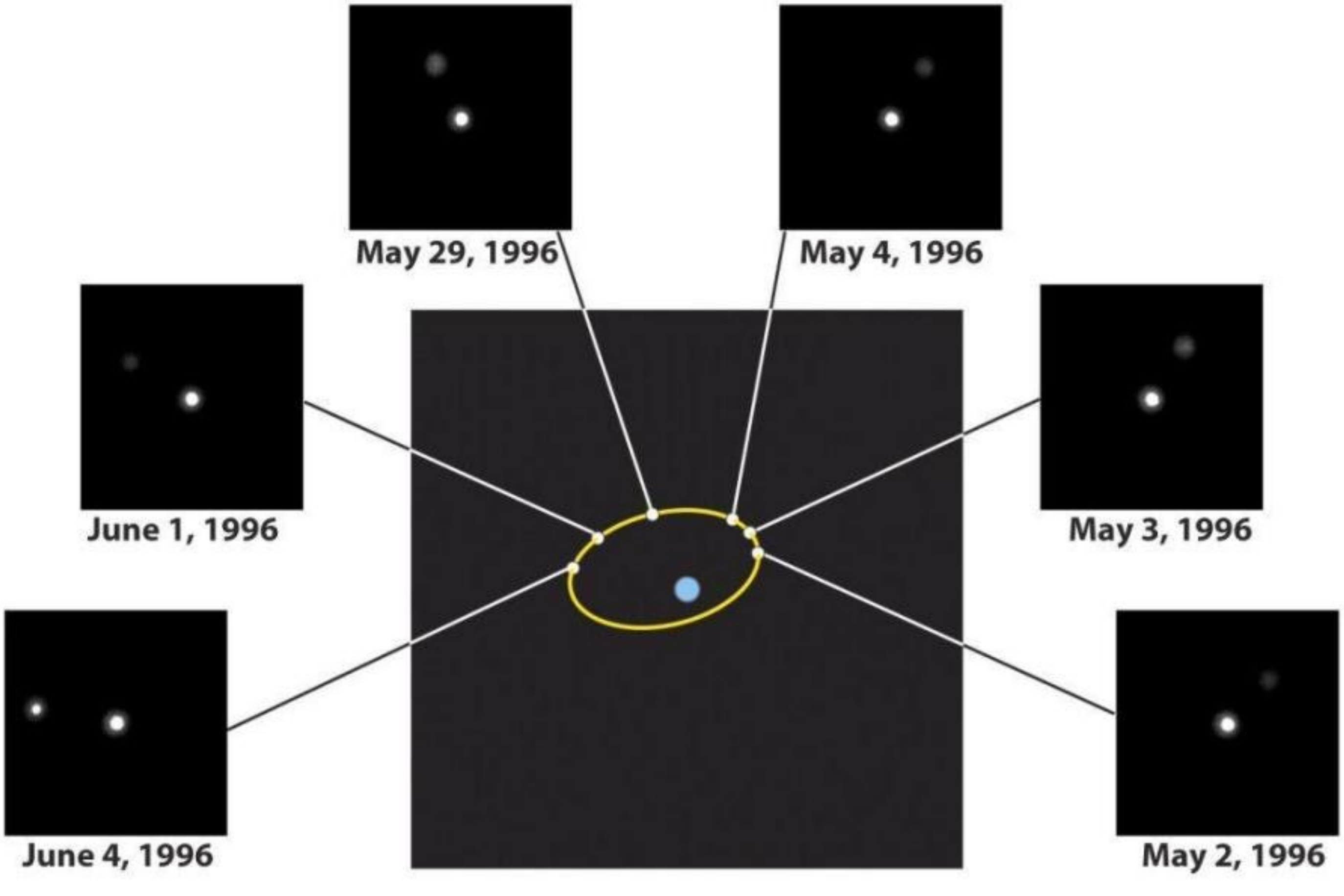
- The huge number of stars
- Colors
- Interstellar gas

How can we describe/classify stars?

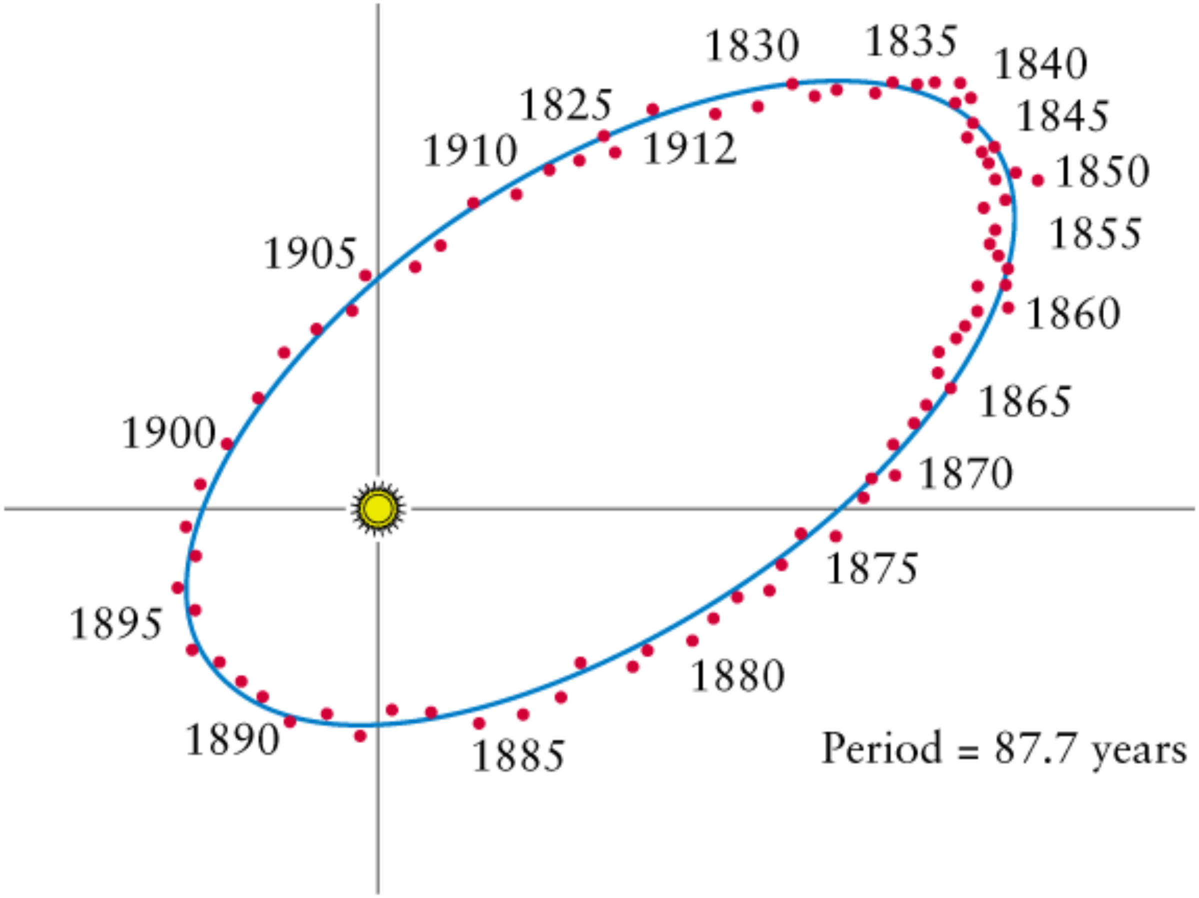
- Temperature
- Luminosity (total energy output)
- Mass (orbital motion)
- Physical sizes
- True motion in space

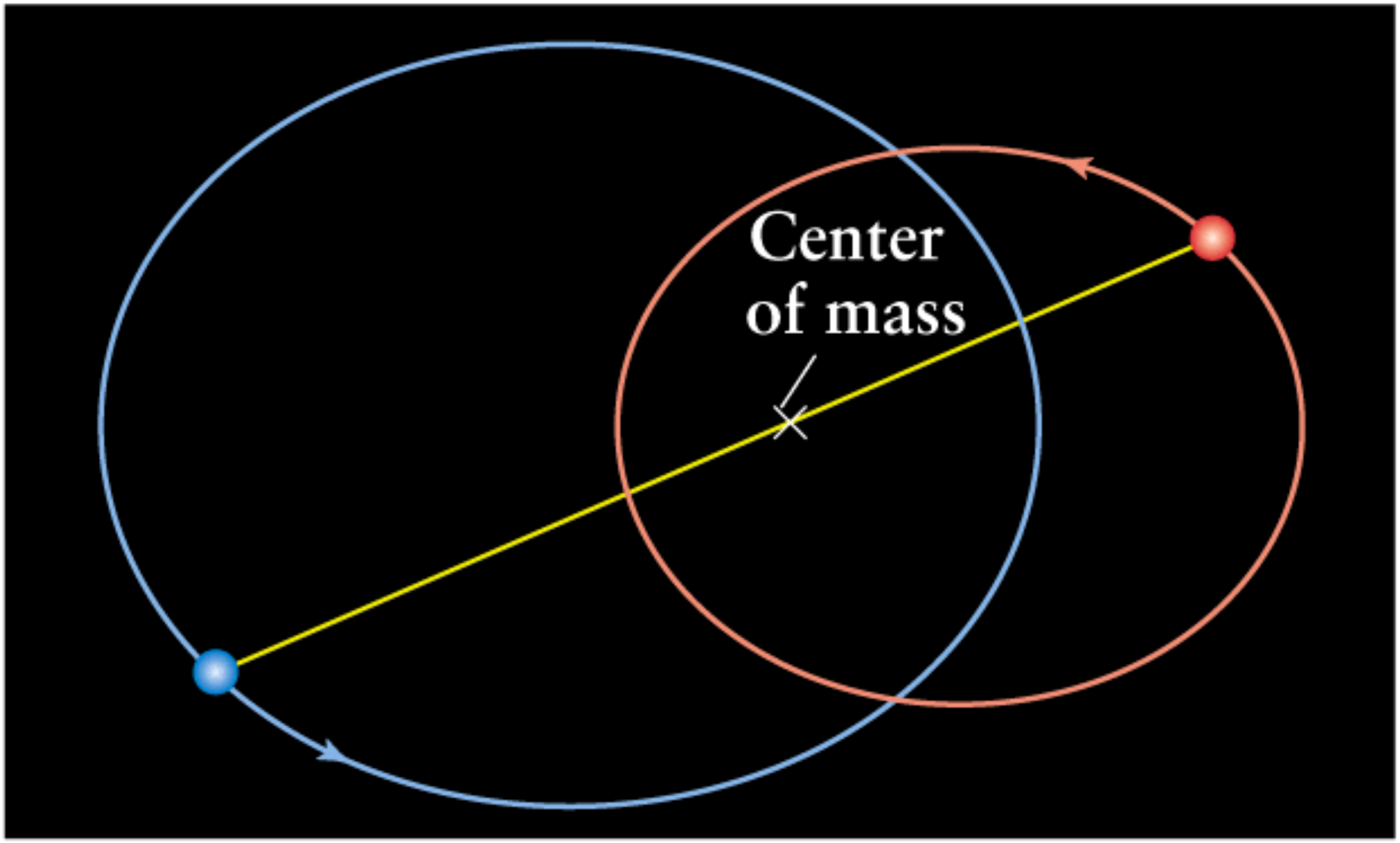
Binary stars

1. Visual binaries - can see both stars. Binaries (any type) always orbit around the mutual center of mass.



Can plot orbit of either star around the other, treated as stationary.





b

$$a_1M_1=a_2M_2$$

where a = semimajor axis, M = mass

Recall semimajor axis = half of the long axis of ellipse

Visual binaries allow direct calculation of stellar masses. Use Kepler's third law:

$$M_1 + M_2 = \frac{a^3}{P^2}$$

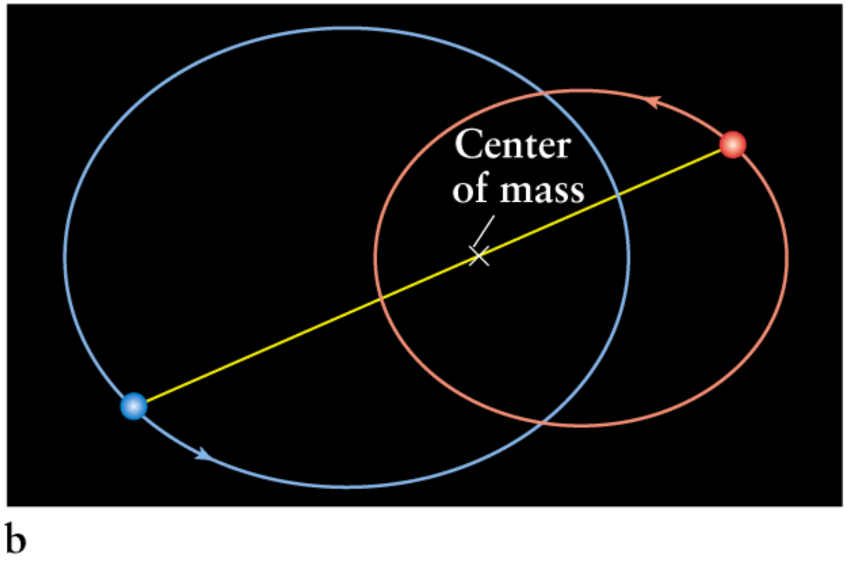
M_1, M_2 are masses of the two stars (in $M_\odot$)

a = semimajor axis of one star's orbit around the other (in units of Earth-Sun distance, AU)

P = orbital period (in years)

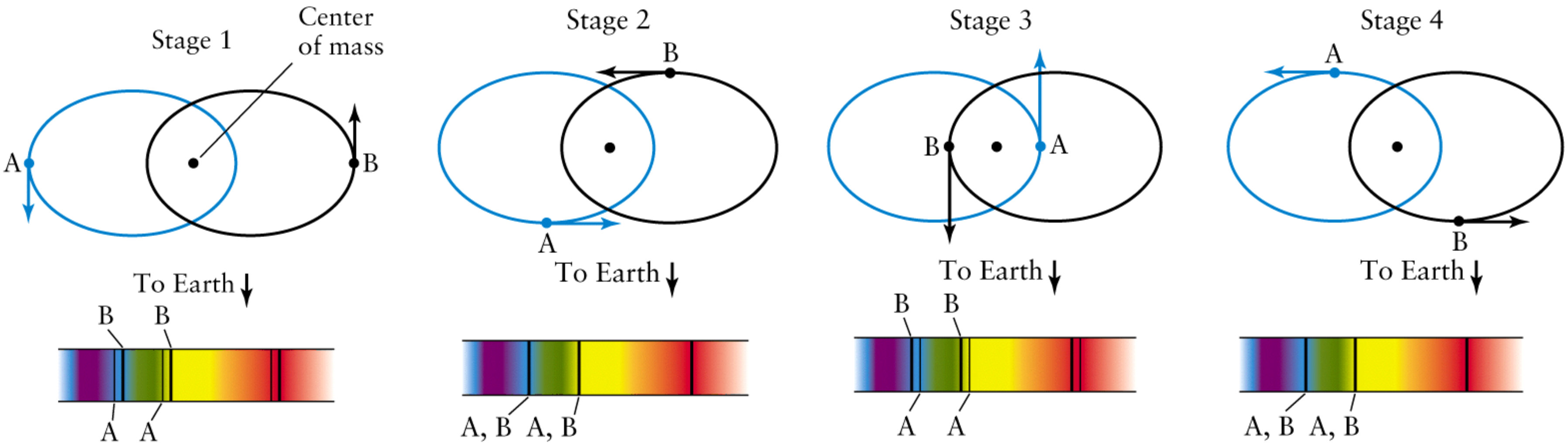
Gives the sum of the masses, not individual masses. Need another equation:
Use fact that the more massive star will be closer to center of mass:

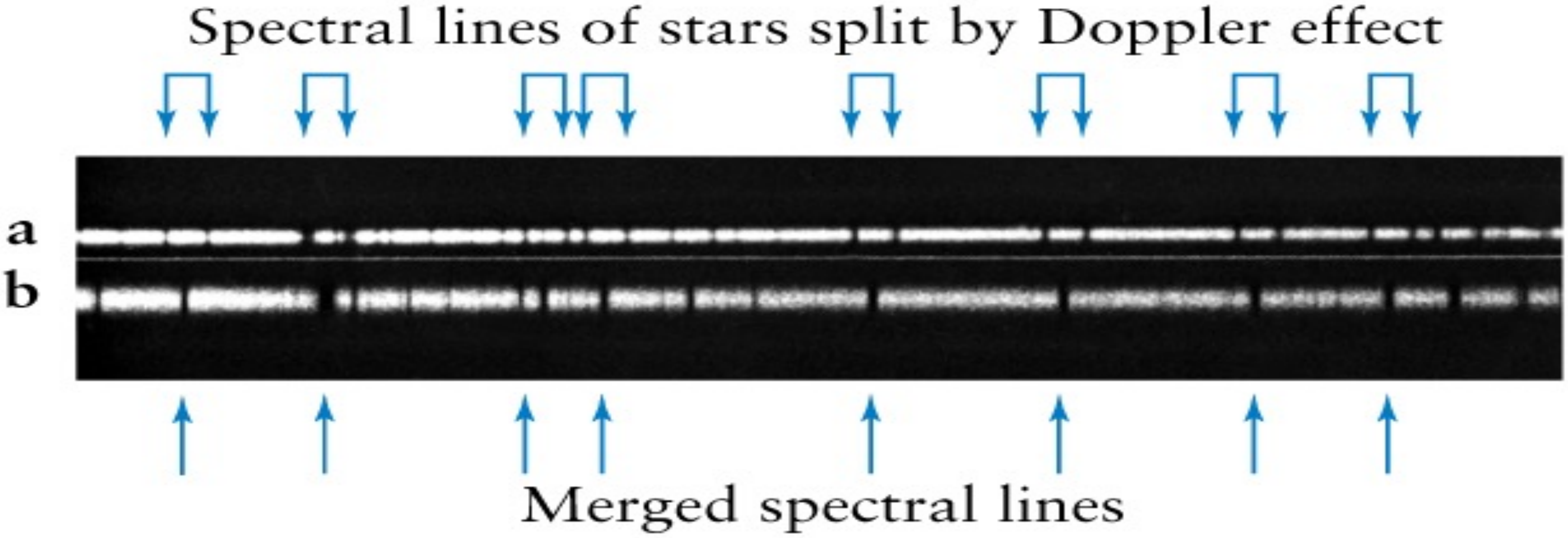
$$\frac{a_2}{a_1} = \frac{M_1}{M_2}$$



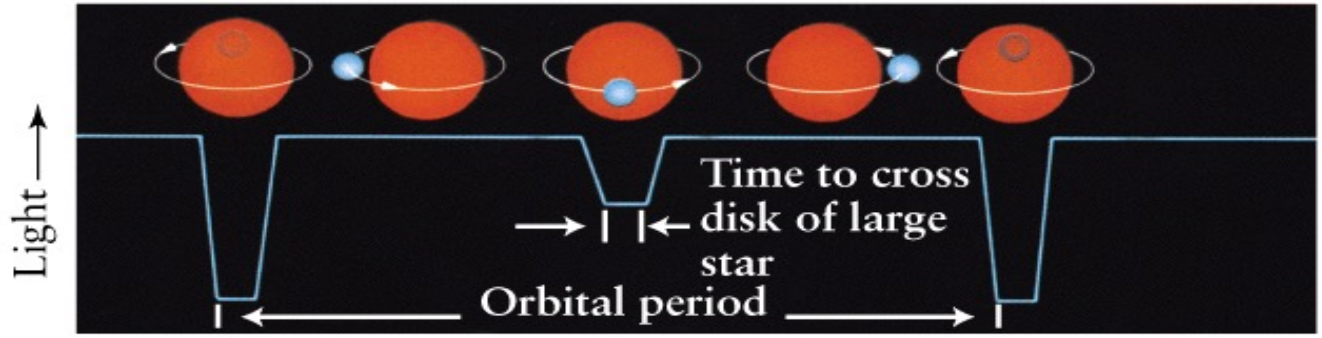
Two equations in two unknowns => can solve for individual masses.

2. Spectroscopic binaries - even if you can't see both stars, might infer binary from spectrum

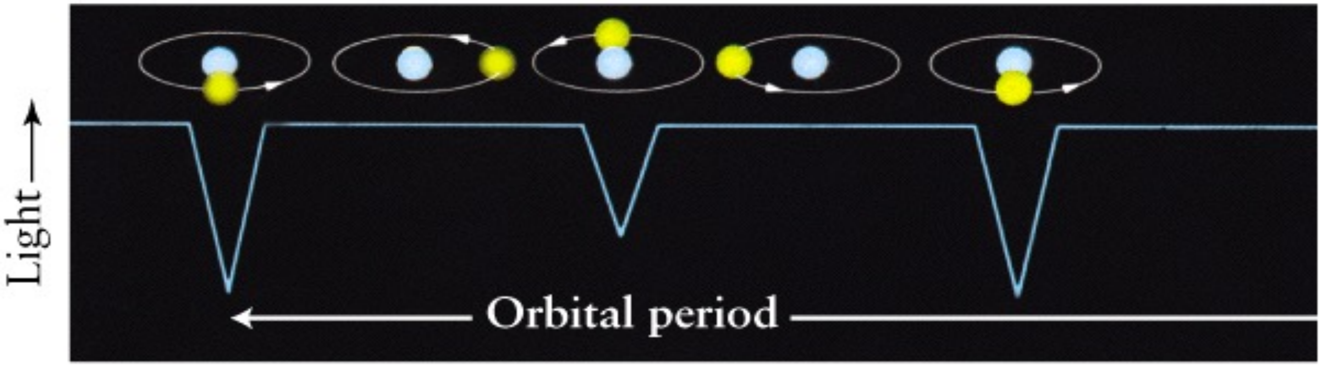




3. Eclipsing binaries - stars periodically eclipse each other. If resolved into 2 stars, can tell it's binary from "light curve" - plot of brightness vs. time.



b Total eclipse



a Partial eclipse

4. Astrometric binaries - one star can be seen, the other can't. The unseen companion makes the visible star "wiggle" on the sky.

Stellar masses and radii

- Masses known for about ~200 stars, within a range of 0.07 - 60 $M_\odot$ (a few of 120 $M_\odot$)

- Radii hard to measure because of large distances (the Sun at 1pc distance has an angular diameter of 9.3milliarcseconds)

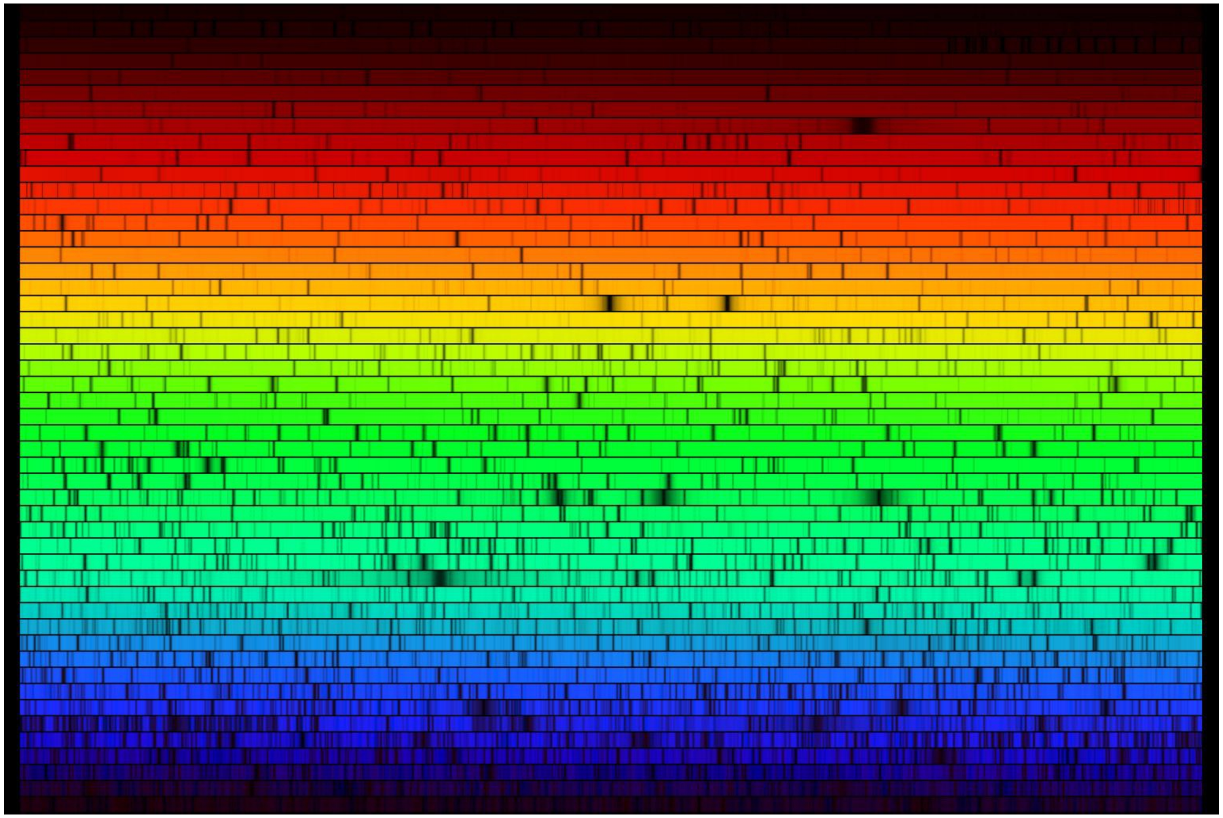
- ~ 600 stars have radii measured directly (interferometry, eclipsing binaries, lunar occultation)

- Recall for a blackbody: $L = 4\pi R^2 \sigma T^4$
  so knowing L and T we can calculate R.

Stars - spectral types

- 1901: Led by Annie Jump Cannon, Harvard astronomers looked at the spectra of >200,000 stars.

- Found that the spectra could be put into relatively few classes (OBAFGKM), based on the relative strengths of the absorption lines of different elements



Mnemonics

Oh Be A Fine Girl Kiss Me

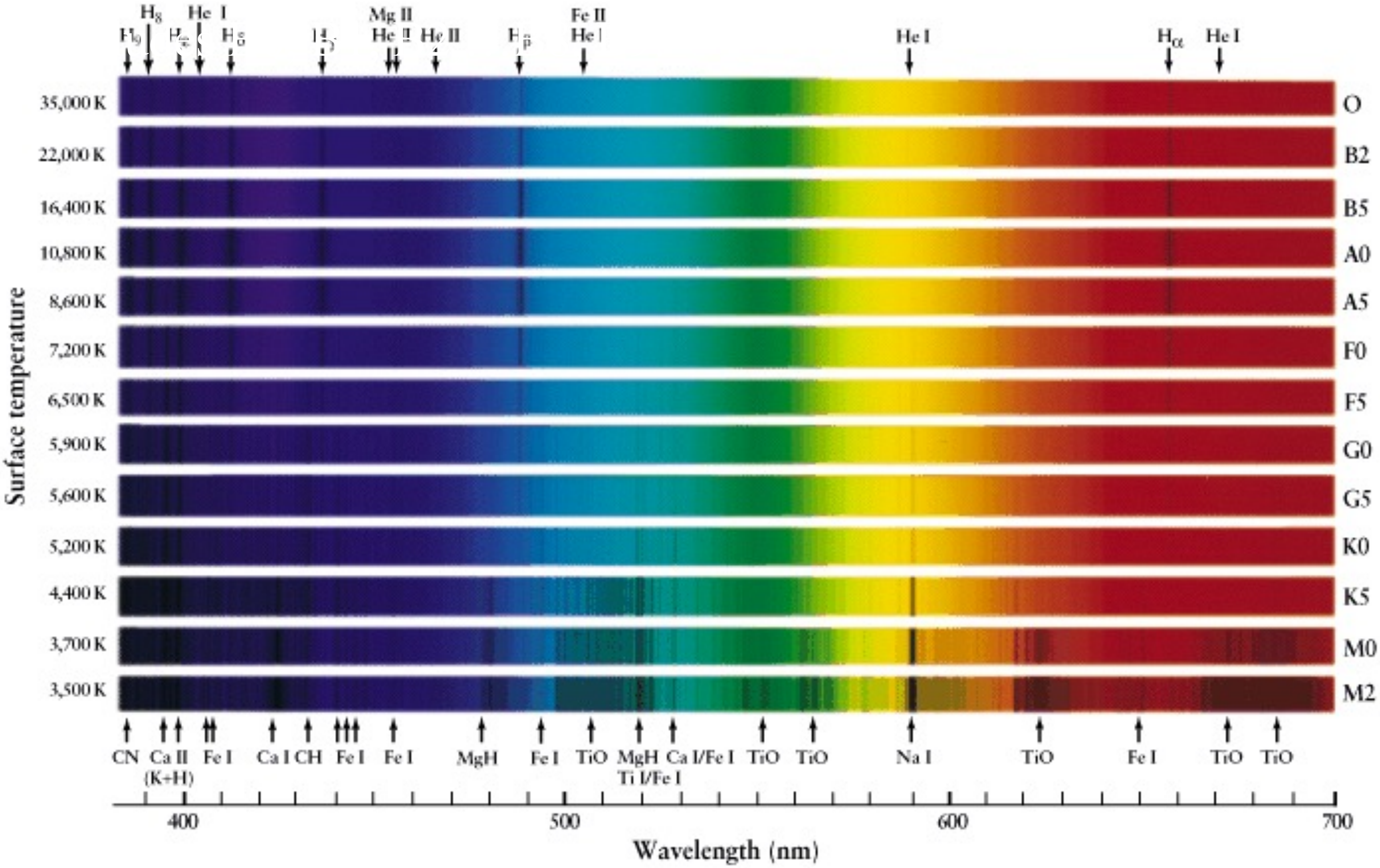
Oh Bother, Another F's Gonna Kill Me

Oh Bother, Astronomers Frequently Give Killer Midterms

One Bug Ate Five Green Killer Moths

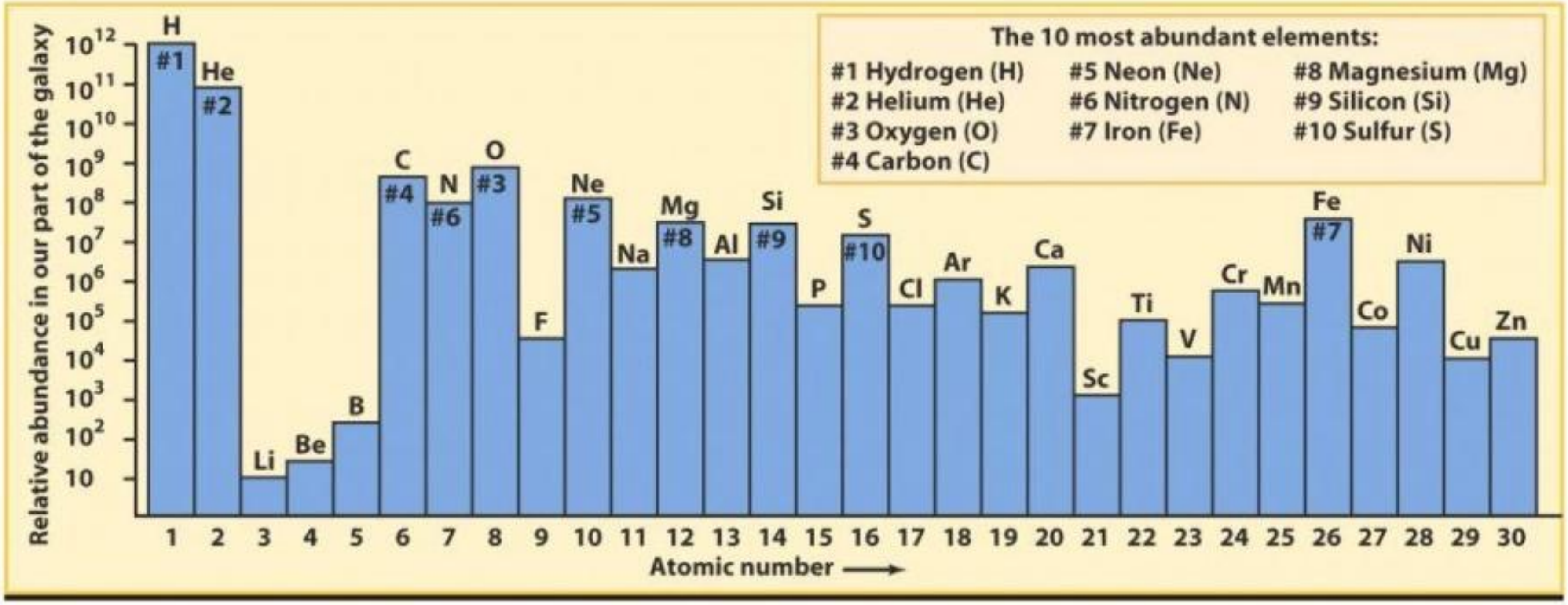
Oven-Baked Ants, Fried Gently, Keeps Moist

Only Boring Astronomers Find Gratification Knowing Mnemonics



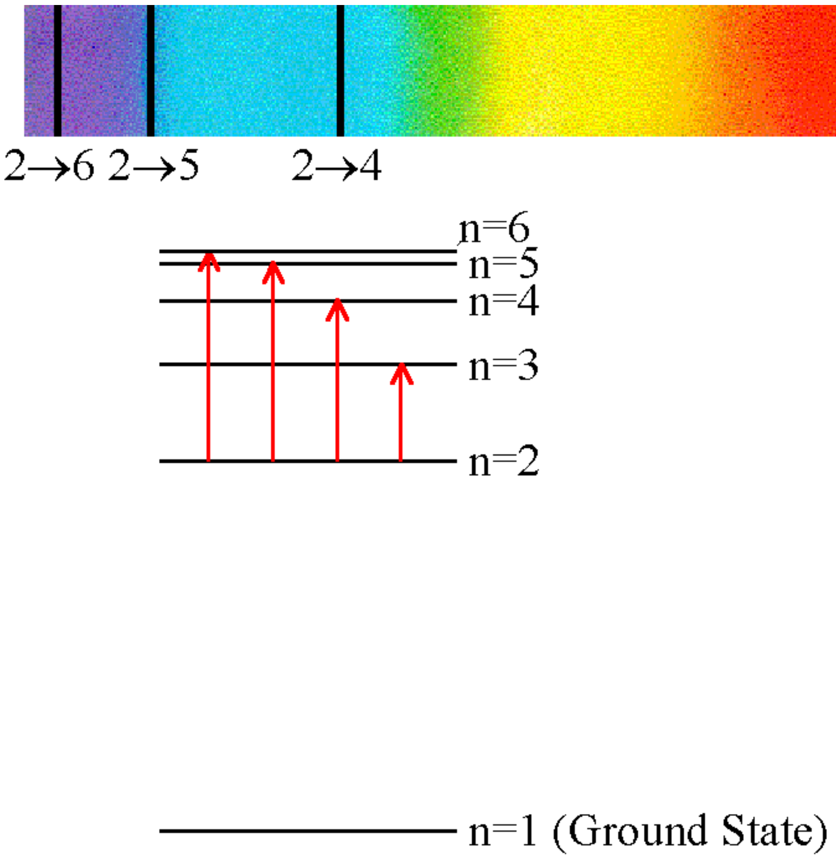
H_9
H_8
H_ϵ
He I
H_δ
H_γ
Mg II
He I
He II
H_β
Fe II
He I
He I
H_α
He I
35,000 K
22,000 K
16,400 K
10,800 K
8,600 K
7,200 K
6,500 K
5,900 K
5,600 K
5,200 K
4,400 K
3,700 K
3,500 K
Surface temperature
O
B2
B5
A0
A5
F0
F5
G0
G5
K0
K5
M0
M2
CN
Ca II (K+H)
Fe I
Ca I
CH
Fe I
Fe I
MgH
Fe I
TiO
MgH Ti I/Fe I
Ca I/Fe I
TiO
TiO
Na I
TiO
Fe I
TiO
TiO
400
500
600
700
Wavelength (nm)

- Are differences in the strengths of the lines from a true difference in abundance of elements?
- NO! The basic cosmic abundance applies to essentially all stars. H and He dominates.
- Almost all stars are about 75% H, 25% He and <1% heavier elements by mass.
- Cosmic abundance: average abundance of elements in the Universe.



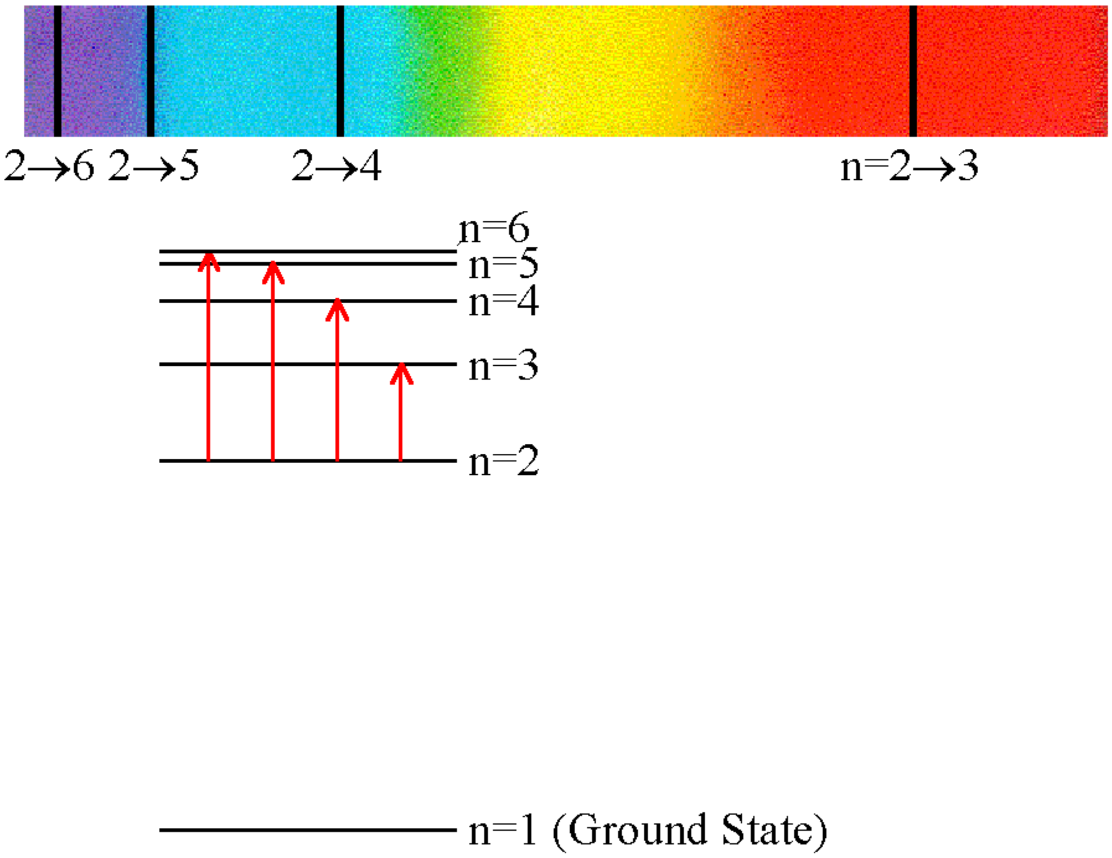
Spectral sequence = temperature sequence

- Stars differ in spectral types due to different temperatures in their photospheres.

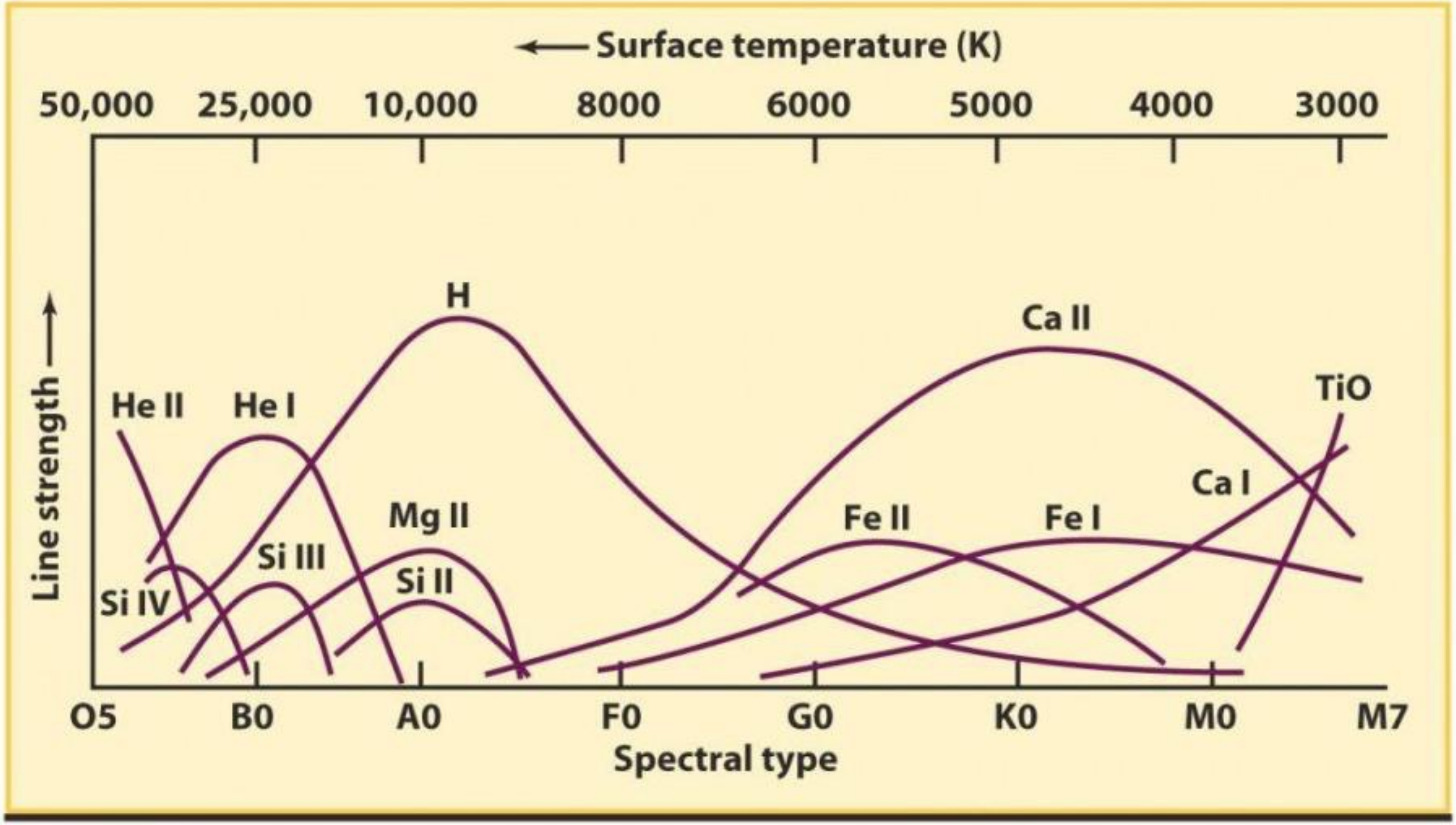


Example hydrogen: if T<10^4 K, most electrons are in the n=1 orbital state => cannot absorb visible light (Balmer photons).

- If T~10^4 K, most electrons are in the n=2 orbital state => can absorb visible light => Balmer absorption lines.
- If T>>10^4 K, most electrons are in level 3 or higher, and cannot absorb visible light.



Balmer lines of hydrogen are most prominent about 10,000 K, peaking around A0. Other lines peak at different temperatures.



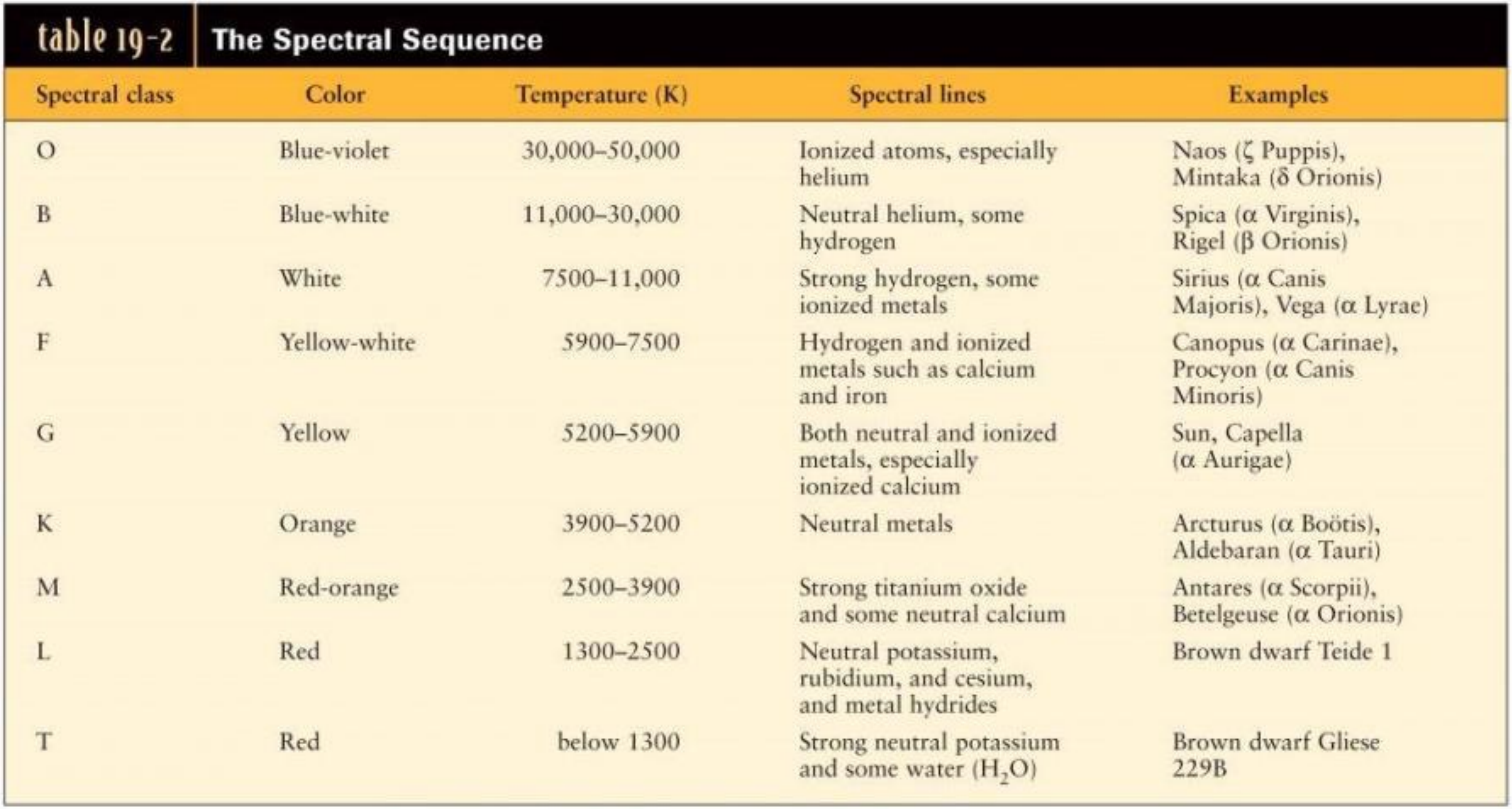


table 19-2 The Spectral Sequence

Spectral class	Color	Temperature (K)	Spectral lines	Examples
O	Blue-violet	30,000–50,000	Ionized atoms, especially helium	Naos (ζ Puppis), Mintaka (δ Orionis)
B	Blue-white	11,000–30,000	Neutral helium, some hydrogen	Spica (α Virginis), Rigel (β Orionis)
A	White	7500–11,000	Strong hydrogen, some ionized metals	Sirius (α Canis Majoris), Vega (α Lyrae)
F	Yellow-white	5900–7500	Hydrogen and ionized metals such as calcium and iron	Canopus (α Carinae), Procyon (α Canis Minoris)
G	Yellow	5200–5900	Both neutral and ionized metals, especially ionized calcium	Sun, Capella (α Aurigae)
K	Orange	3900–5200	Neutral metals	Arcturus (α Boötis), Aldebaran (α Tauri)
M	Red-orange	2500–3900	Strong titanium oxide and some neutral calcium	Antares (α Scorpii), Betelgeuse (α Orionis)
L	Red	1300–2500	Neutral potassium, rubidium, and cesium, and metal hydrides	Brown dwarf Teide 1
T	Red	below 1300	Strong neutral potassium and some water (H_2O)	Brown dwarf Gliese 229B

Stellar classification provides a mean to estimate physical characteristics of stars.

What we know so far about stars:

- Distances
- True 3-D motion
- Absolute magnitude/luminosities
- Color/Spectral type/Temperature
- Mass (for some)

=> synthesize this information into the H-R diagram.